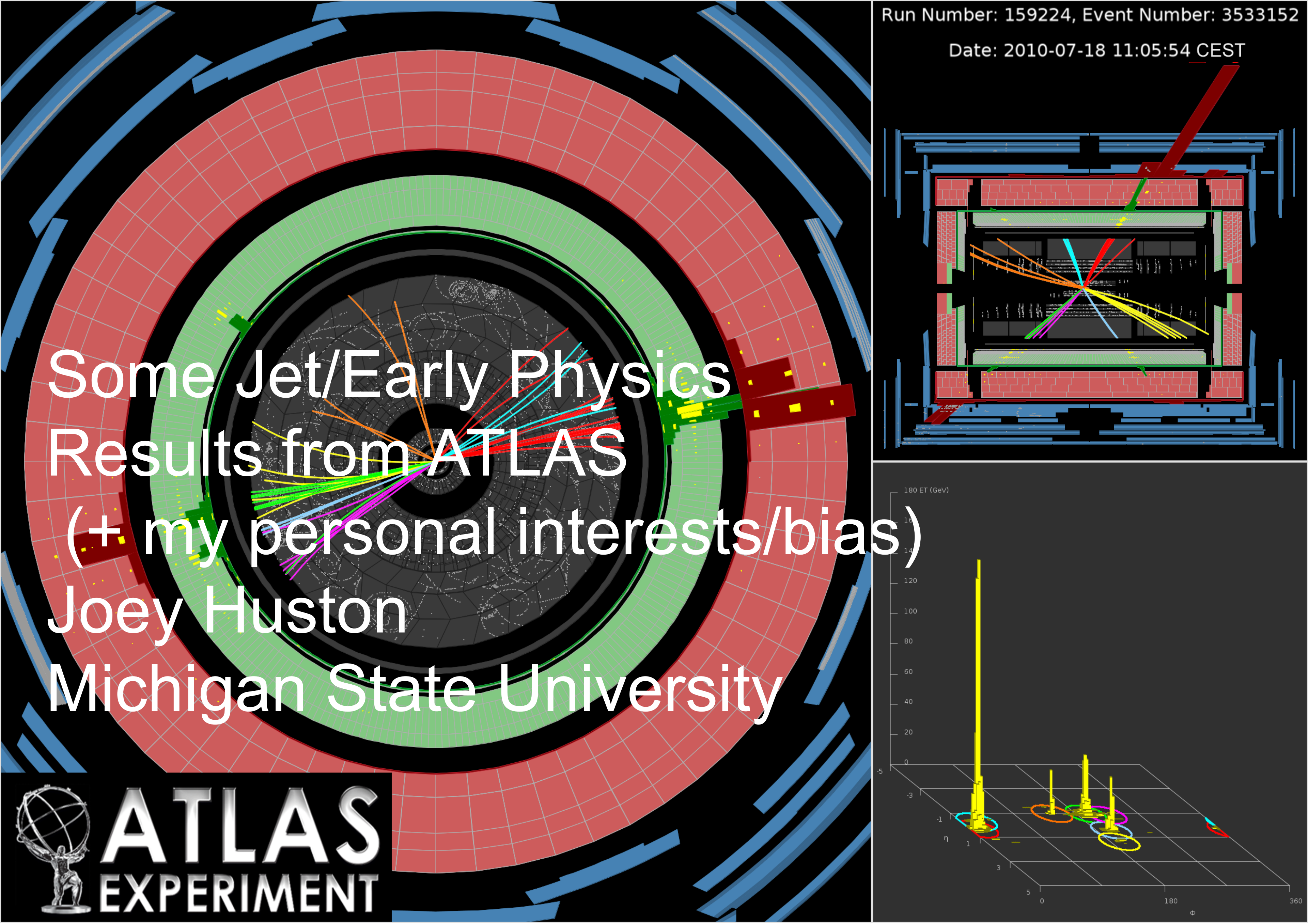
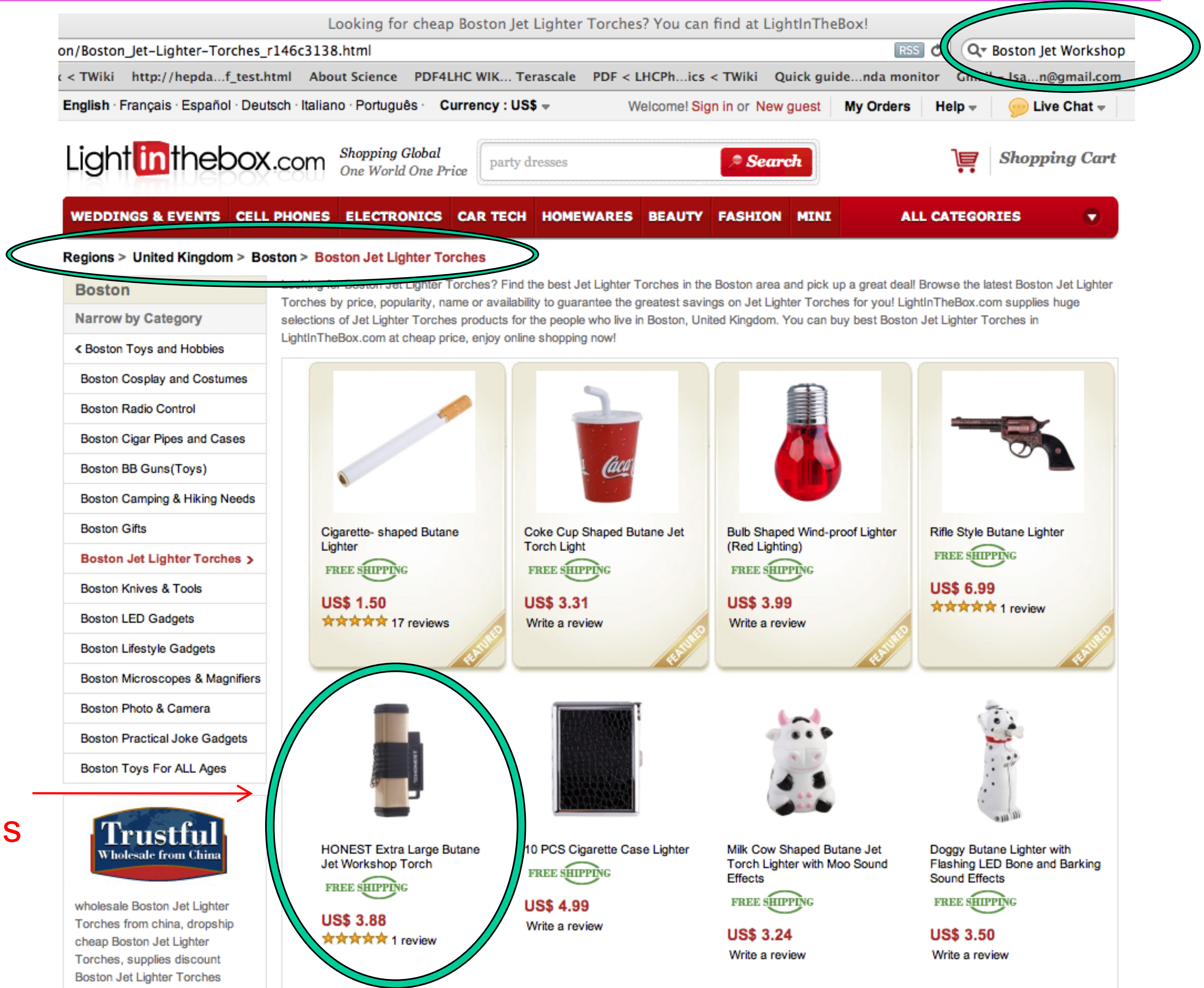


Some Jet/Early Physics Results from ATLAS
(+ my personal interests/bias)

Joey Huston
Michigan State University

Boston Jet Workshop Jan. 12-14

Google search on ‘Boston Jet Workshop’



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Boston Jet Workshop

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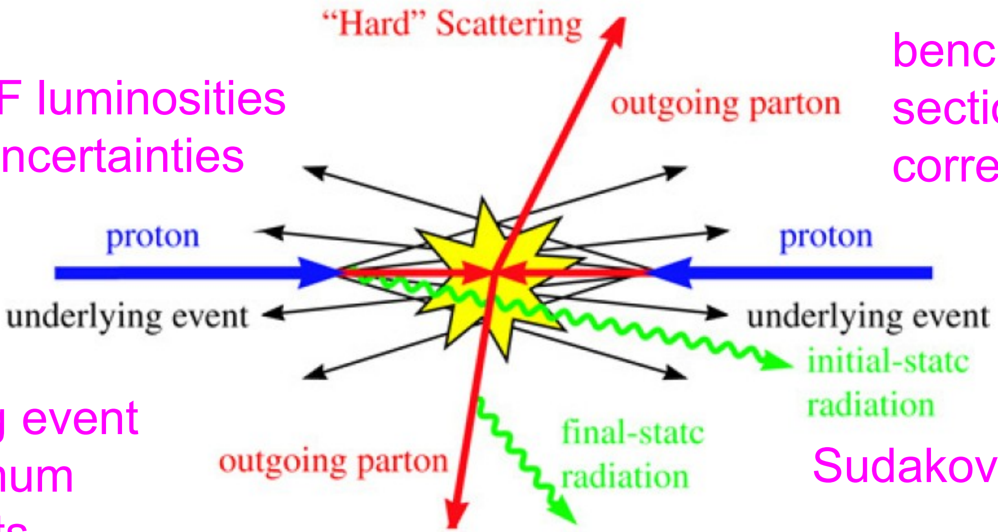
now we know what they’re going to give us instead of a backpack →

Rediscovering the Standard Model

(my phrase by the way: circa 2004)



LO, NLO and NNLO calculations
K-factors

PDF's, PDF luminosities and PDF uncertainties

benchmark cross sections and pdf correlations

underlying event and minimum bias events

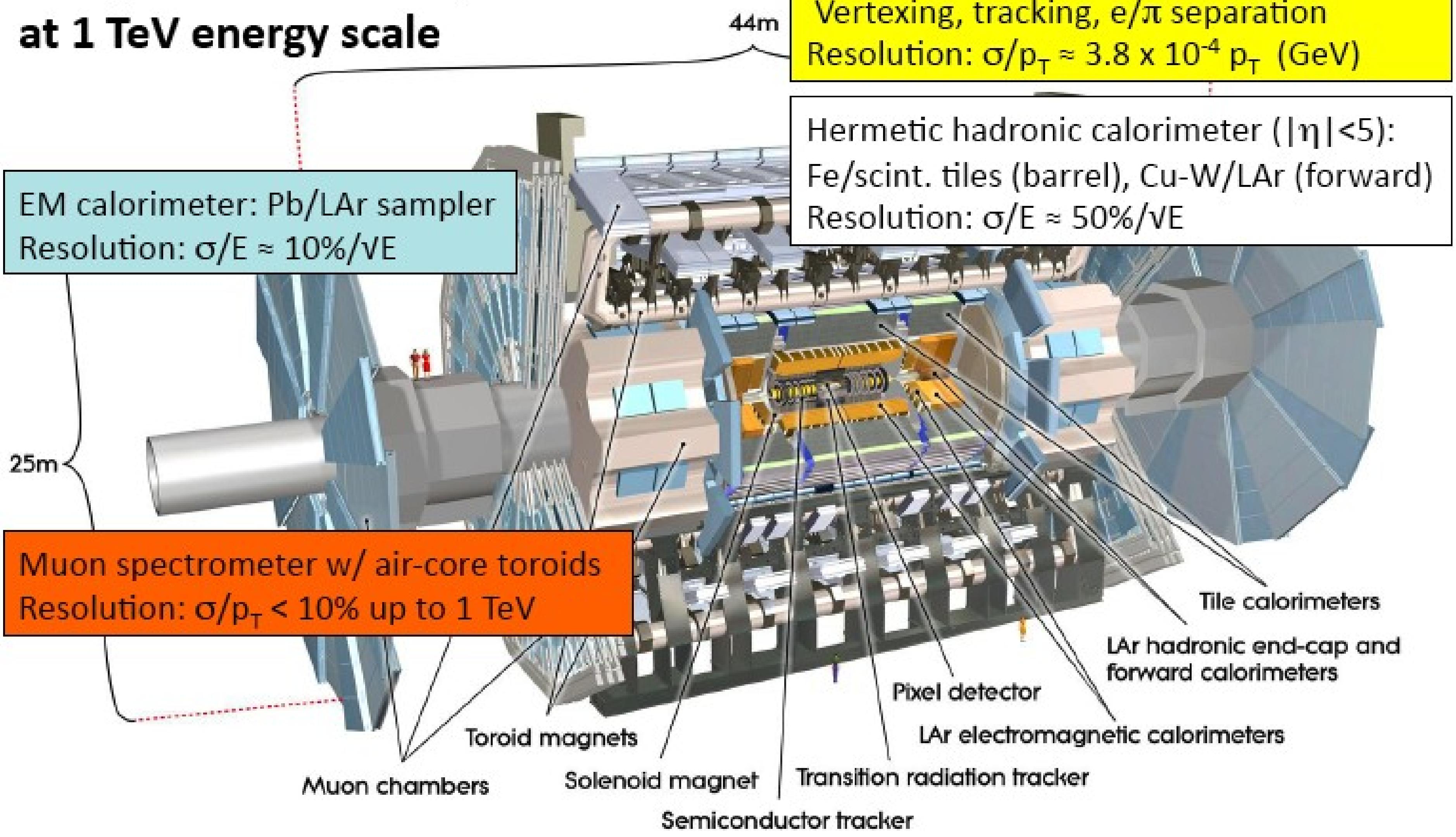
Sudakov form factors

jet algorithms and jet reconstruction

First results for underlying event, minimum bias, photons, leptons, jets, missing E_T, benchmark cross sections (W/Z, W/Z + jets, top)

ATLAS detector

Designed for discovery at 1 TeV energy scale



Inner detector: Si strips/pixels;TRT straws)
Vertexing, tracking, e/π separation
Resolution: $\sigma/p_T \approx 3.8 \times 10^{-4}\, p_T$ (GeV)

Hermetic hadronic calorimeter ($|\eta|<5$):
Fe/scint. tiles (barrel), Cu-W/LAr (forward)
Resolution: $\sigma/E \approx 50\%/\sqrt{E}$

EM calorimeter: Pb/LAr sampler
Resolution: $\sigma/E \approx 10\%/\sqrt{E}$

Muon spectrometer w/ air-core toroids
Resolution: $\sigma/p_T < 10\%$ up to 1 TeV

ATLAS detector

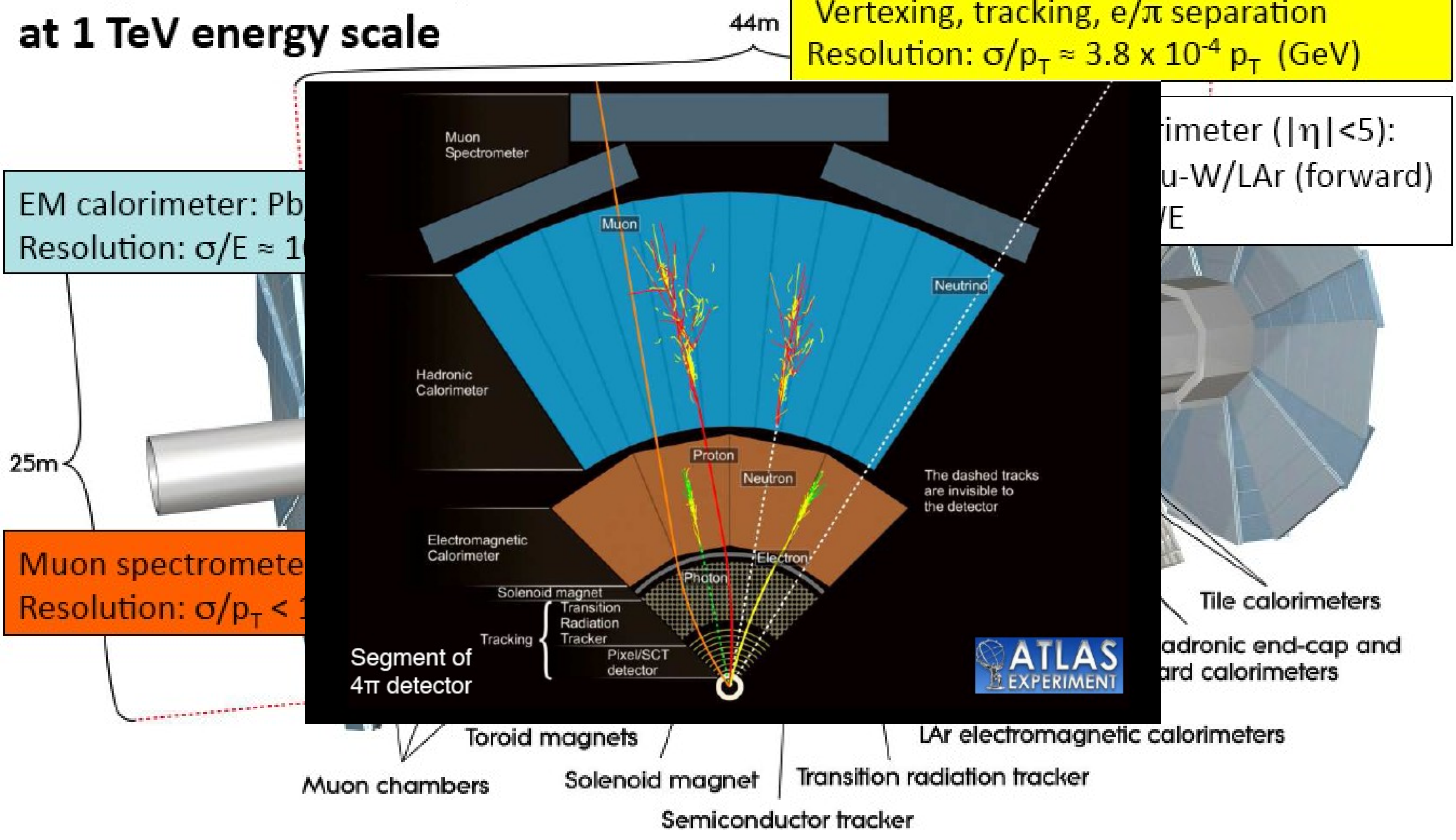
Designed for discovery at 1 TeV energy scale

Inner detector: Si strips/pixels;TRT straws)
Vertexing, tracking, e/π separation
Resolution: $\sigma/p_T \approx 3.8 \times 10^{-4}\, p_T$ (GeV)

imeter ($|\eta|<5$):
u-W/LAr (forward)
/E

EM calorimeter: Pb
Resolution: $\sigma/E \approx 1$

Muon spectromete
Resolution: $\sigma/p_T < 1$

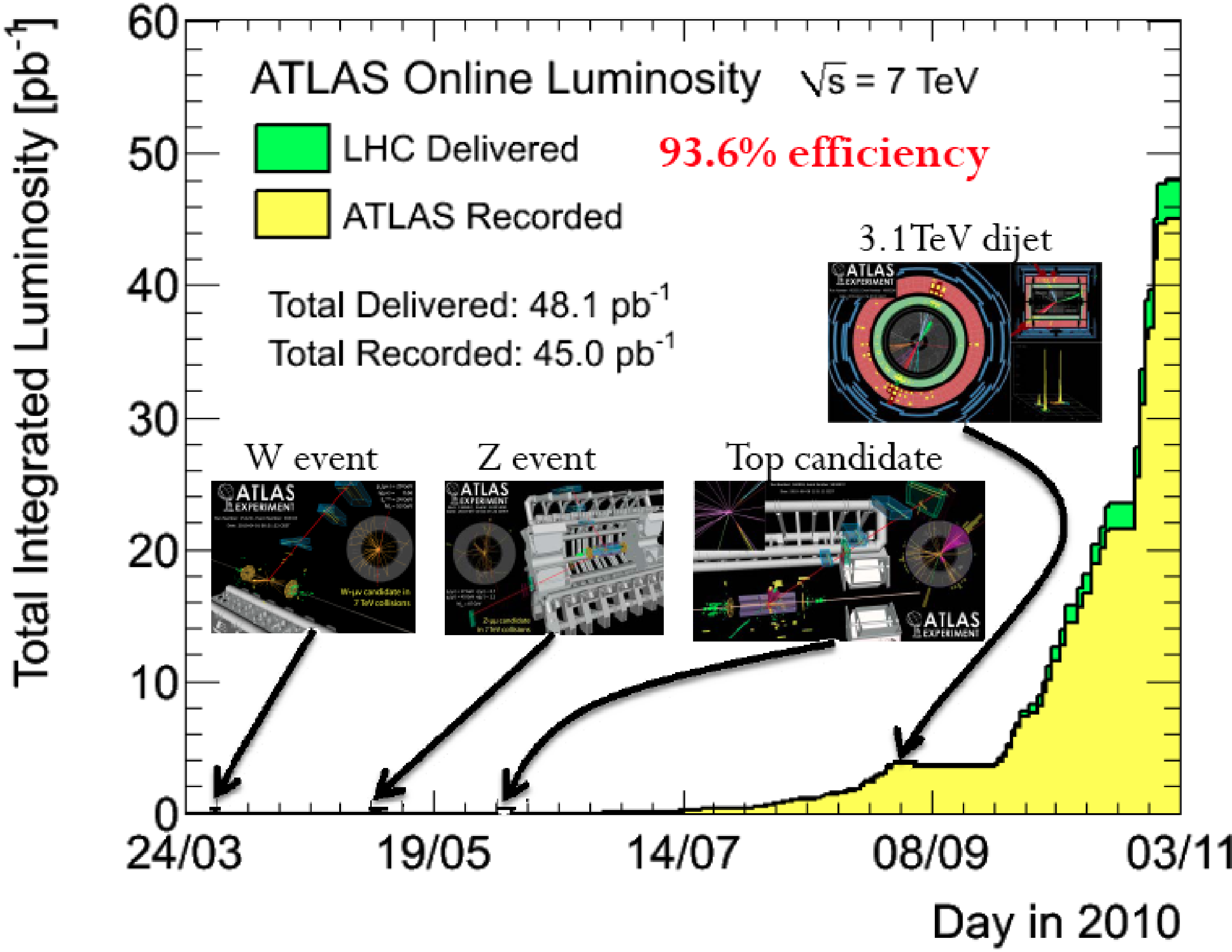


ATLAS physics

- Results with up to 3 pb^{-1}

online luminosity calibrated with dedicated van der Meer scans (see ATLAS-CONF-2010-060)

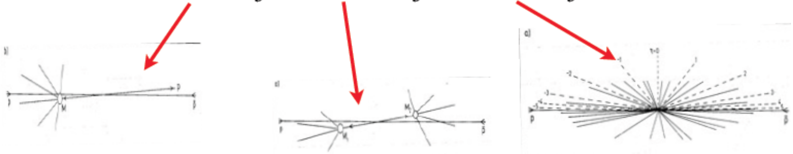
luminosity uncertainty ~11%



All subdectors operating at >97%

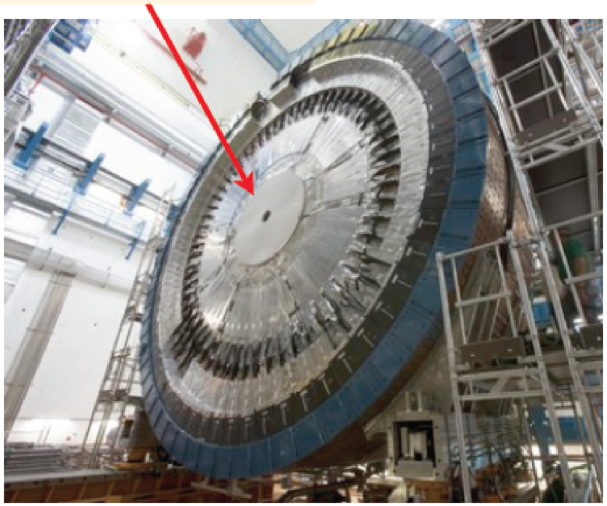
Measuring min bias events in ATLAS

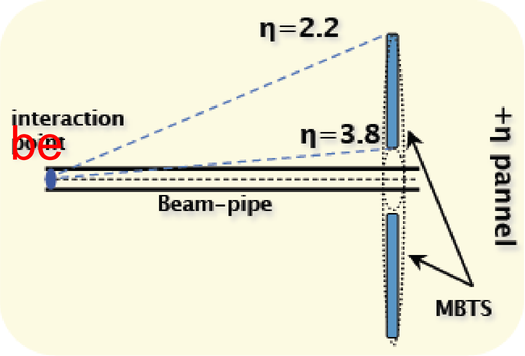
$$\sigma_{tot} = \sigma_{elas} + \sigma_{s.dif} + \sigma_{d.dif} + \sigma_{n.dif}$$



- Data: Arthur Moraes CTEQ-LPC workshop
  - – 900 GeV sample: ~455K events (PLB March'10)
  - – 7 TeV sample: ~370K (ATLAS-CONF-2010-024) & ~10M (ATLAS-CONF-2010-046) events
- Event selection:
  - – Single-arm trigger: require ≥ 1 MBTS counter to fire on either side
  - – At least one primary vertex reconstructed
  - – No additional primary vertices
  - – Require: ≥1 track, $p_T > 500$MeV (ATLAS-CONF-2010-024) or ≥2 tracks, $p_T > 100$MeV (ATLAS-CONF-2010-046), $|\eta| < 2.5$

Minimum Bias Trigger Scintilators (MBTS)





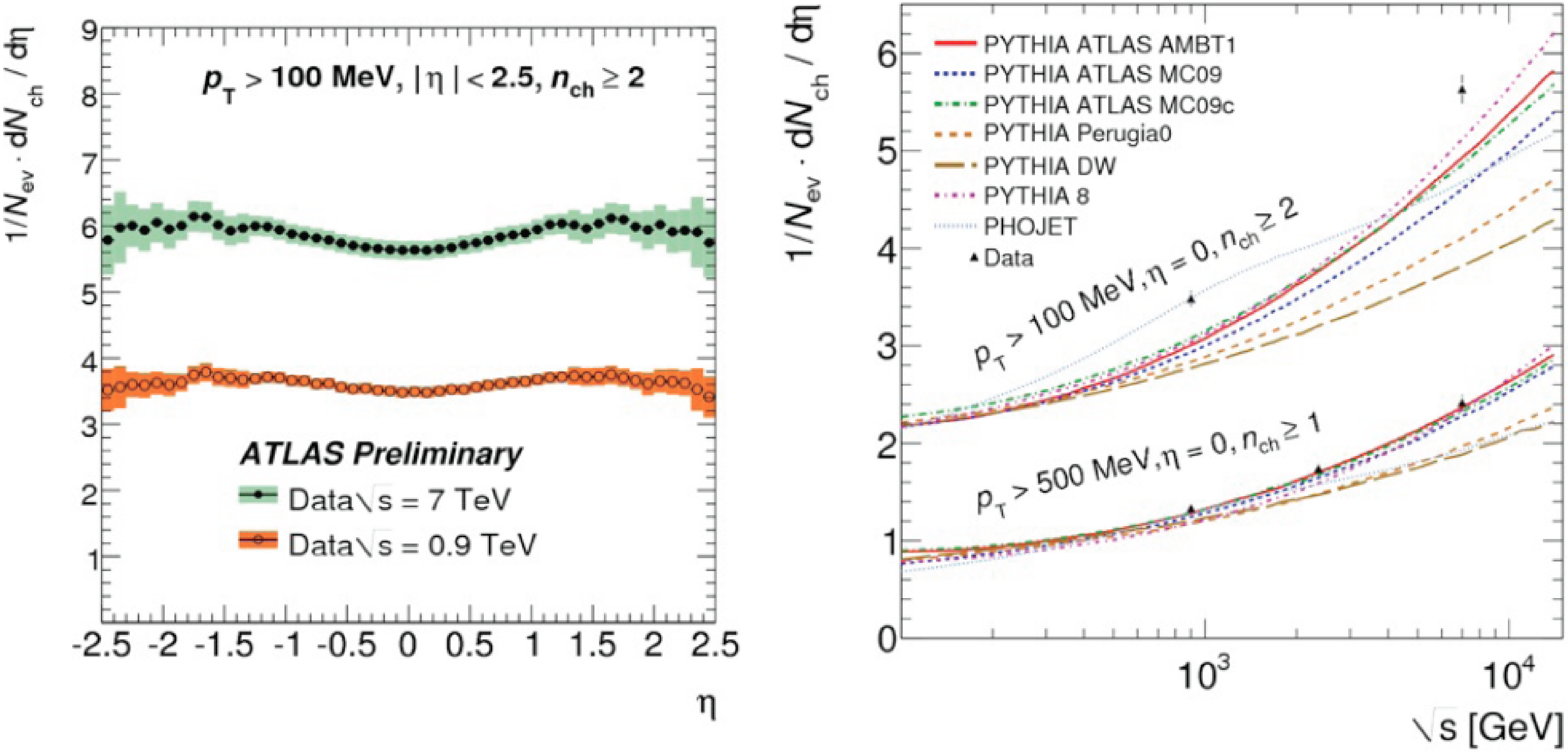
…so minimum bias is basically what you define it to be

Trigger efficiency ~99% (slightly lower for low-p_T analysis)

Cosmic ray background < 10^{-6} and beam backgrounds <0.1%

Pile-up removal ~0.2%, residual rate from pile-up ~0.01%

Track multiplicities at 900 GeV and 7 TeV

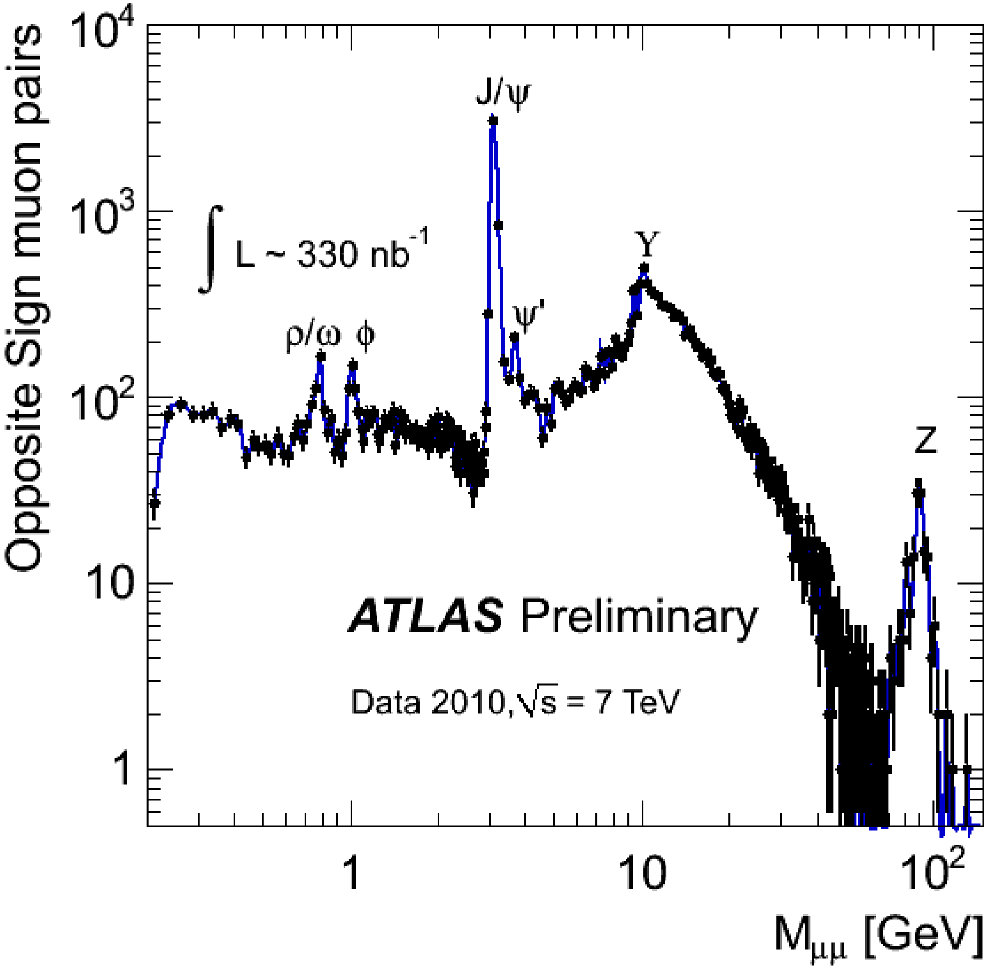


- Major improvement: track p_T threshold reduced from 500MeV to 100MeV (probing softer particle production). Measurements at 7TeV were made over a much larger sample (~10M events) than in the previous analysis.

ATLAS-CONF-2010-046

Leptons: dimuon mass spectrum

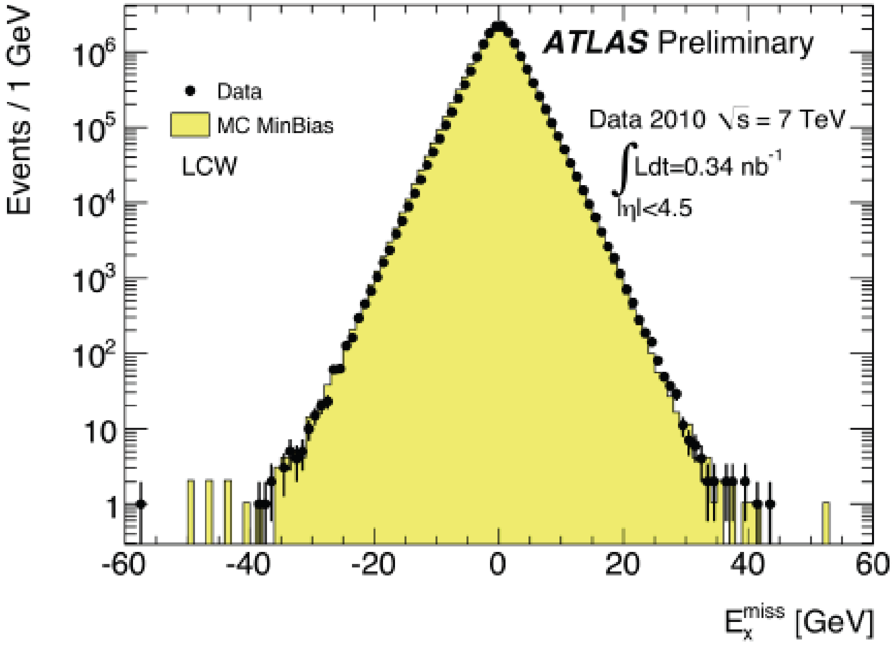
- Opposite sign muons reconstructed in both inner detector and muon spectrometer, using 6 GeV/c muon trigger
- Dimuon mass spectrum mapped across 3 orders of magnitude from ~100 MeV to ~200 GeV

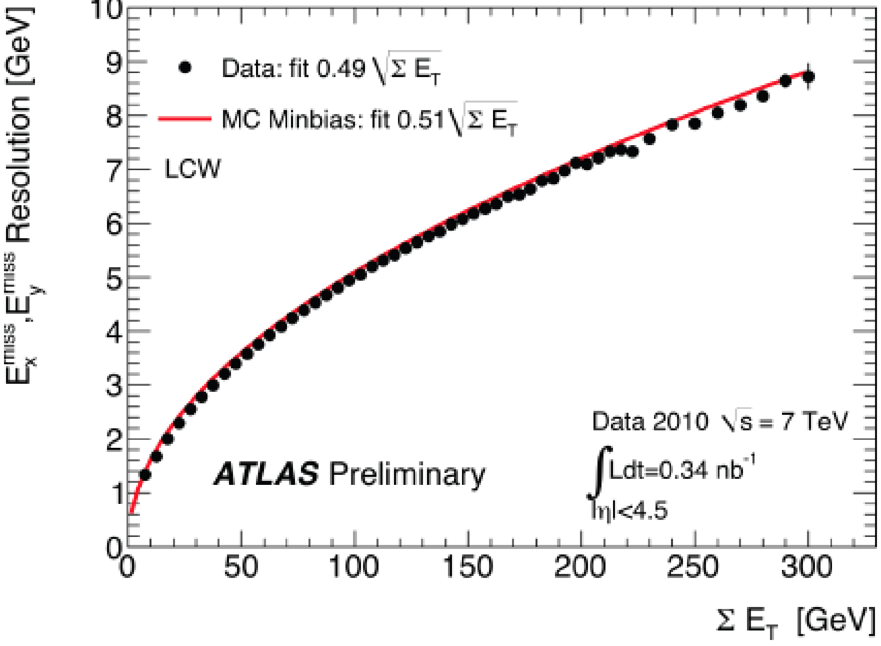


Missing E_T resolution

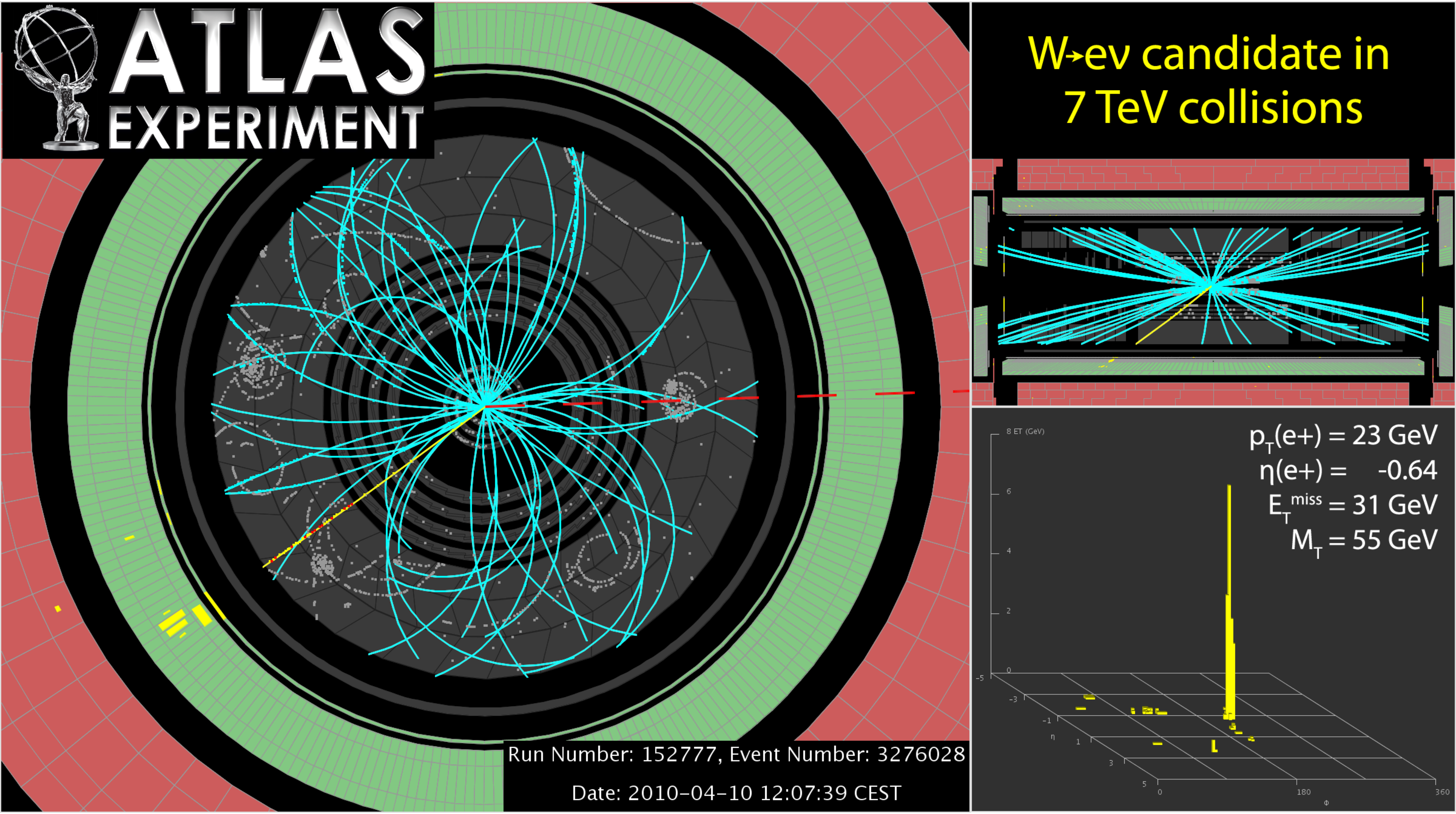
- Best resolution needed to detect presence of neutrinos/non-interacting particles from new physics
- Using topological clusters of calorimeter cells, with calibration determined for each component based on estimate of hadronic component

Resolutions measured on 15 million selected minimum bias events at 7 TeV





Leptons + missing E_T: W/Z production

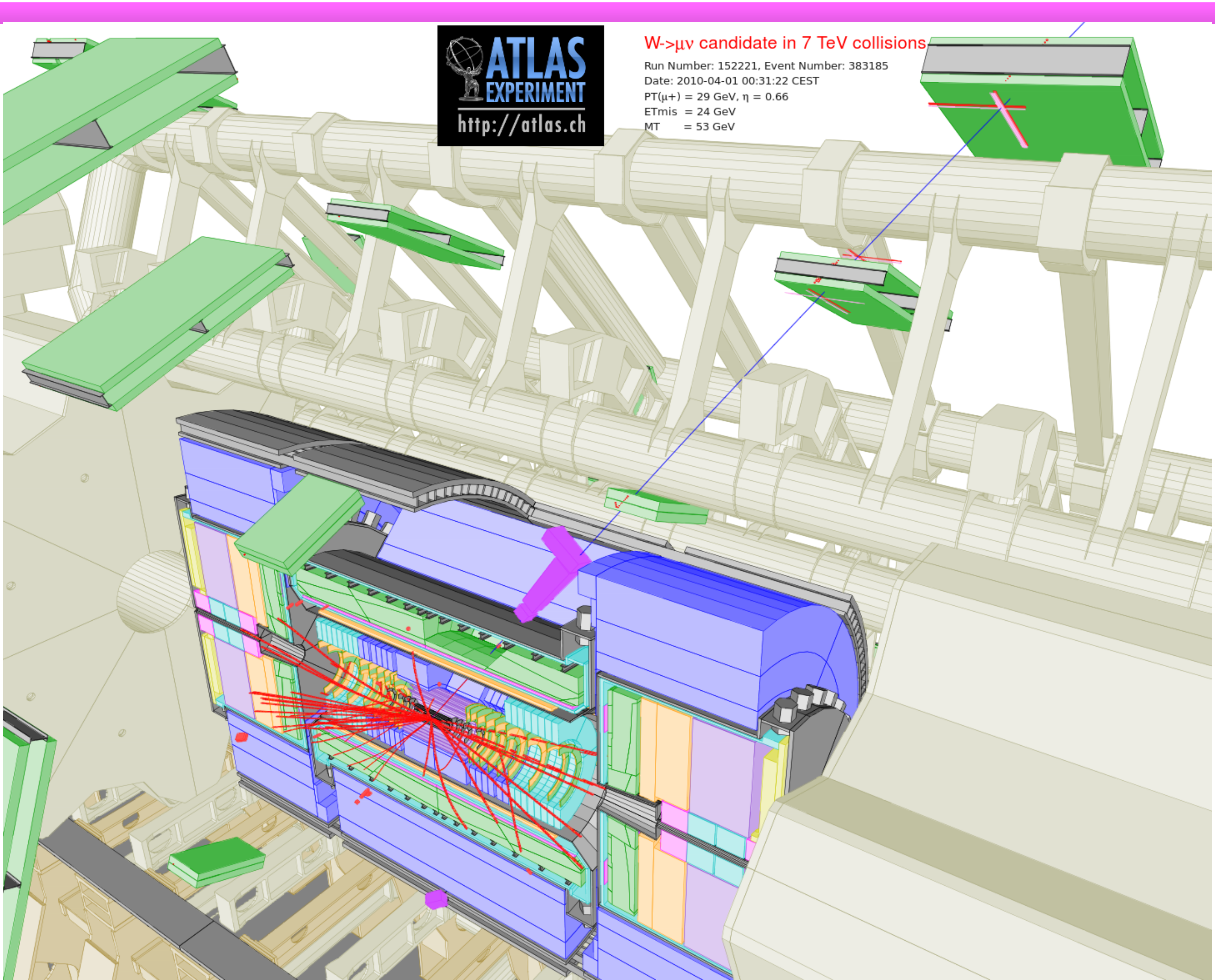


W→eν candidate in 7 TeV collisions

$p_T(e+) = 23$ GeV
$\eta(e+) = -0.64$
$E_T^{miss} = 31$ GeV
$M_T = 55$ GeV

Run Number: 152777, Event Number: 3276028
Date: 2010-04-10 12:07:39 CEST

Leptons + missing E_T: W/Z production



W->μν candidate in 7 TeV collisions

Run Number: 152221, Event Number: 383185

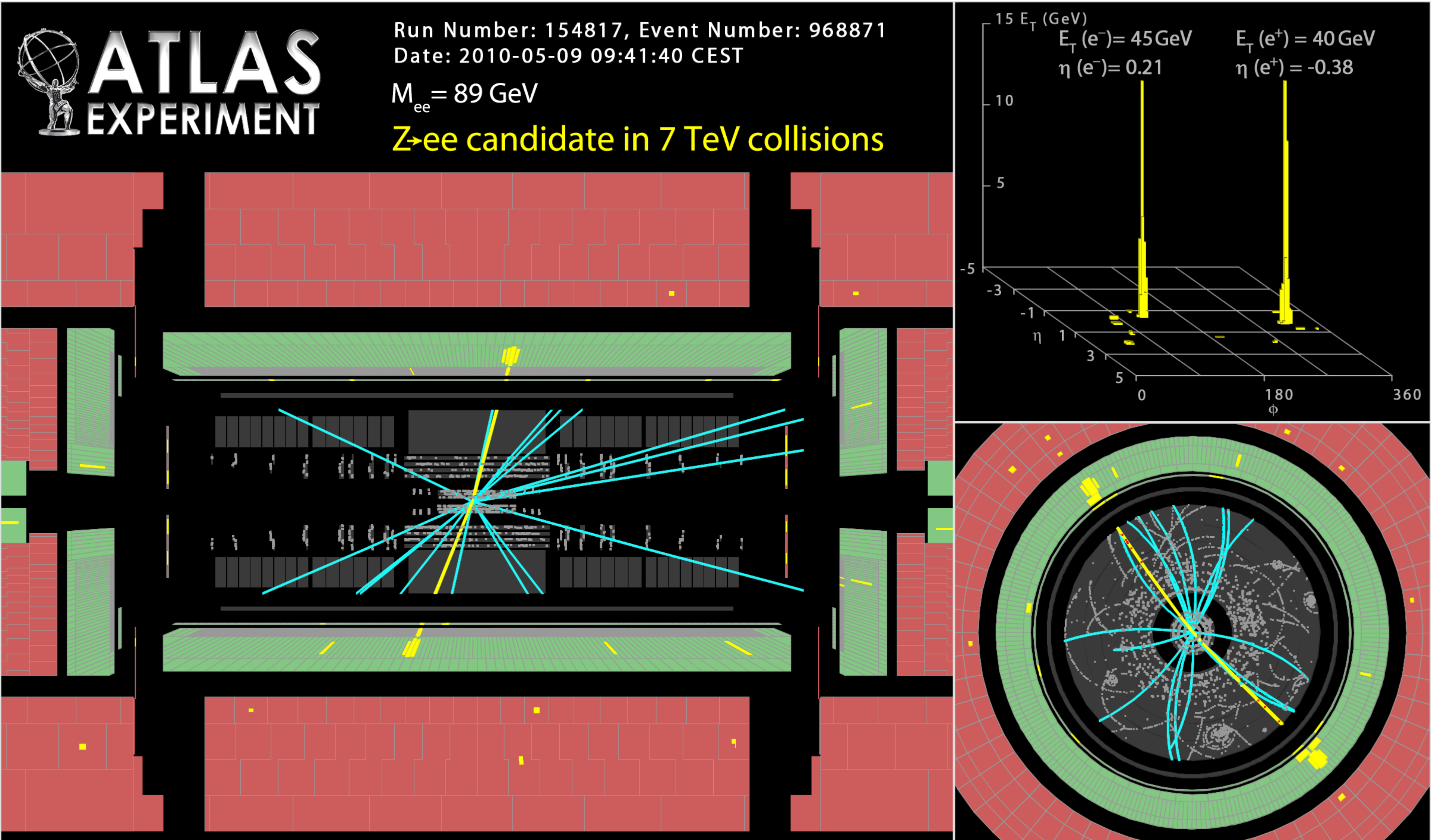
Date: 2010-04-01 00:31:22 CEST

PT(μ+) = 29 GeV, η = 0.66

ETmis = 24 GeV

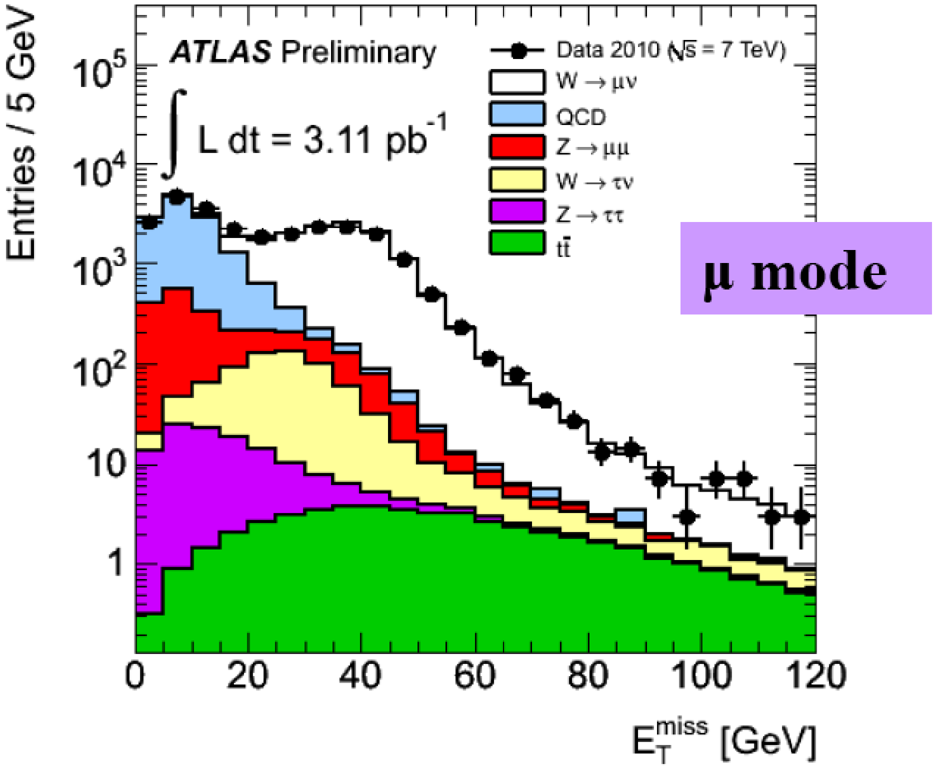
MT = 53 GeV

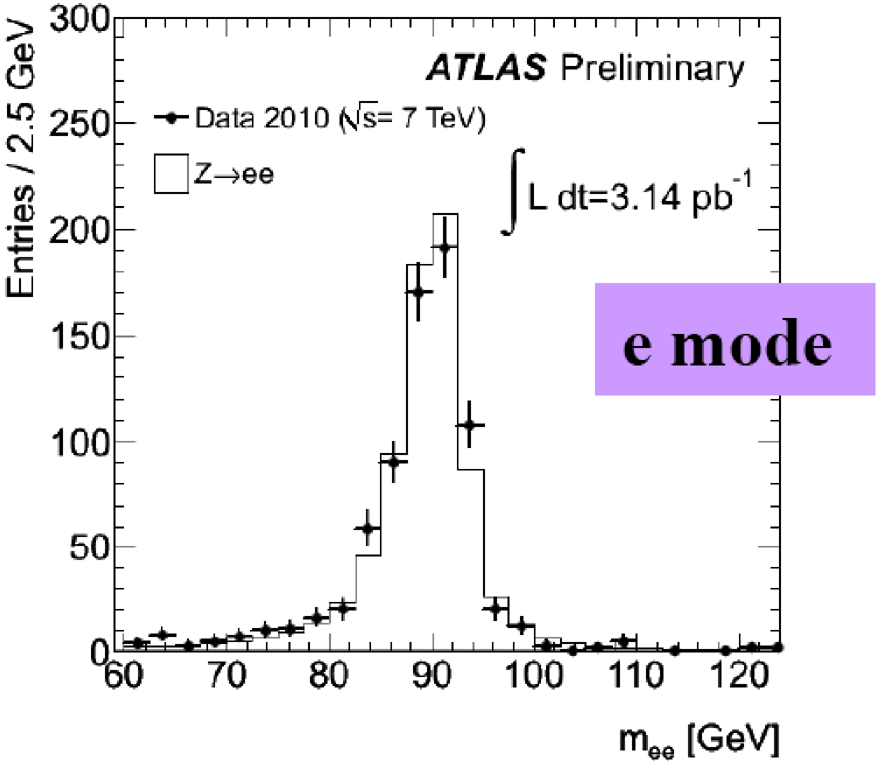
$Z \to e^+e^-$


ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_{ee} = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
E_T (e^-)= 45 GeV
η (e^-)= 0.21
E_T (e^+) = 40 GeV
η (e^+) = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
φ

W and Z rediscovery: these are the primary benchmark cross sections

- W
  - e(μ) E_T>20 GeV; $|\eta|$<2.5 (2.4)
  - missing E_T > 25 GeV
  - transverse mass > 40 GeV
- Z
  - e(μ) E_T>20 GeV; $|\eta|$<2.5 (2.4)
  - 66 < m_{ll} < 116 GeV





W/Z p_T distributions

- BFKL effects may broaden the p_T distributions for W and Z production (at least in some kinematics regions)
- But, expect broader p_T distributions at LHC than at Tevatron from DGLAP alone (lower x partons, more phase space for gluon emission)

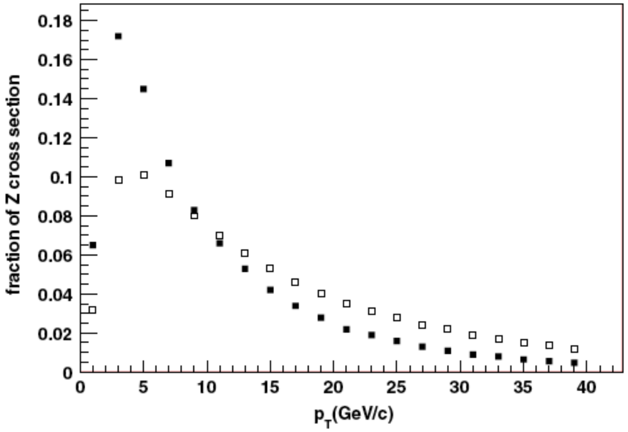
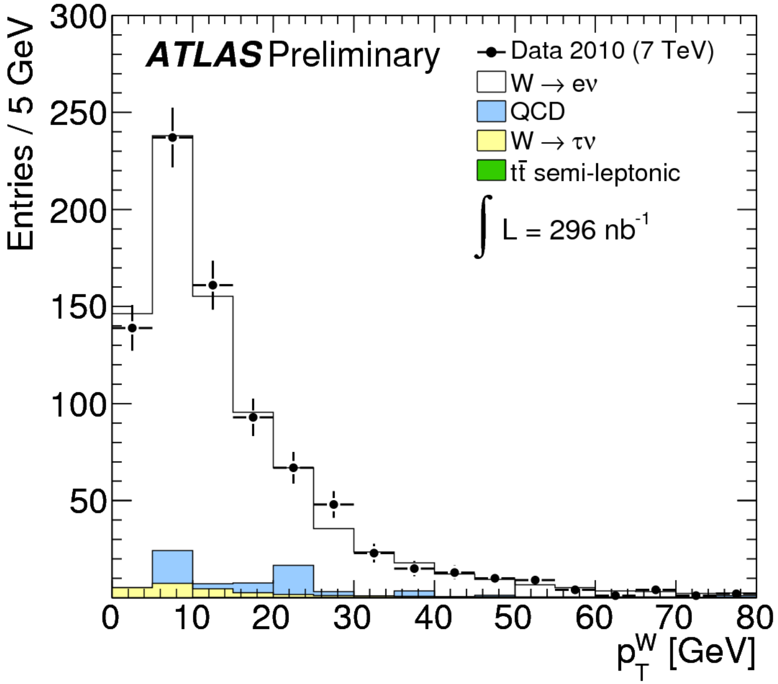
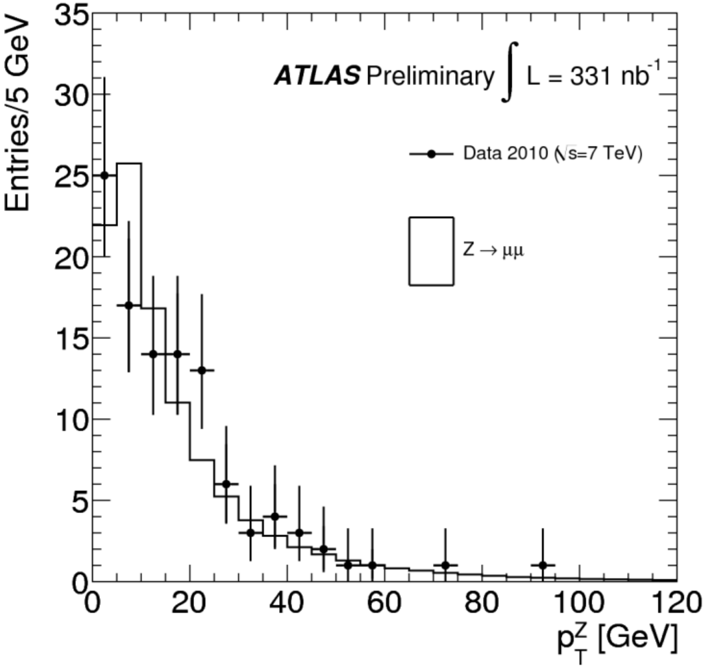


Figure 89. Predictions for the transverse momentum distributions for *Z* production at the Tevatron (solid squares) and LHC (open squares).





W/Z cross sections

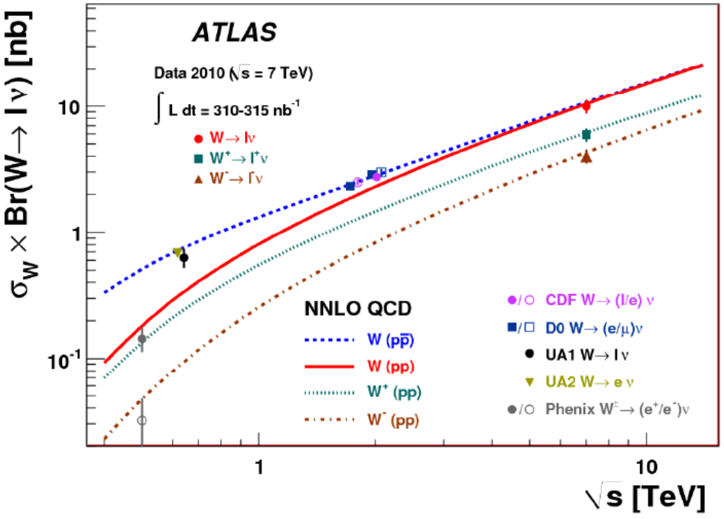
$$\sigma_W^{tot} \bullet BR(W \to l\nu) = 9.96 \pm 0.23(stat) \pm 0.50(syst) \pm 1.10(lumi)\,nb$$

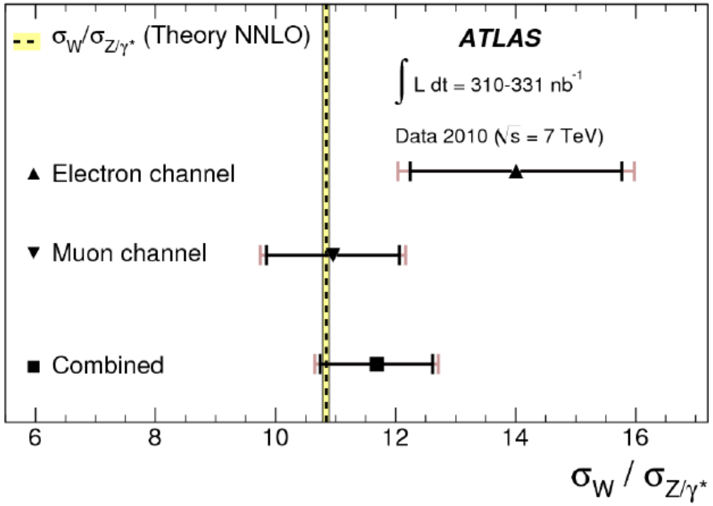
$$\sigma_Z^{tot} \bullet BR(Z/\gamma^* \to ll) = 0.82 \pm 0.06(stat) \pm 0.05(syst) \pm 0.09(lumi)\,nb$$

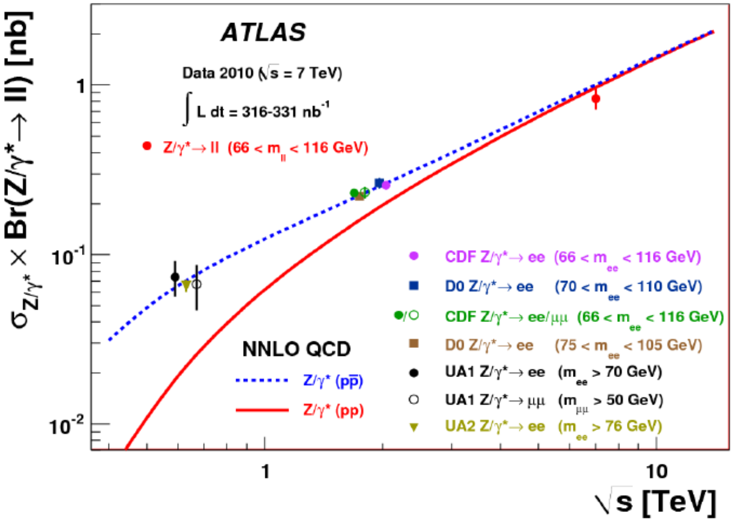
($66<m_{ll}<116$ GeV window)

arXiv:1010.2130 (accepted by JHEP)

- In reasonable agreement with NNLO predictions for 7 TeV, but still statistics and systematics limited
  - plus the current 11% luminosity uncertainty
- Both will improve with more data: W and Z will be one of SM benchmark cross sections





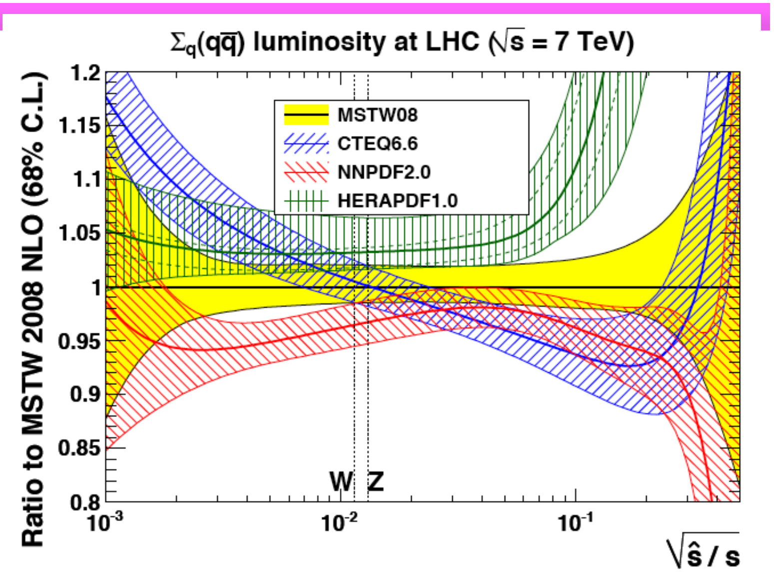


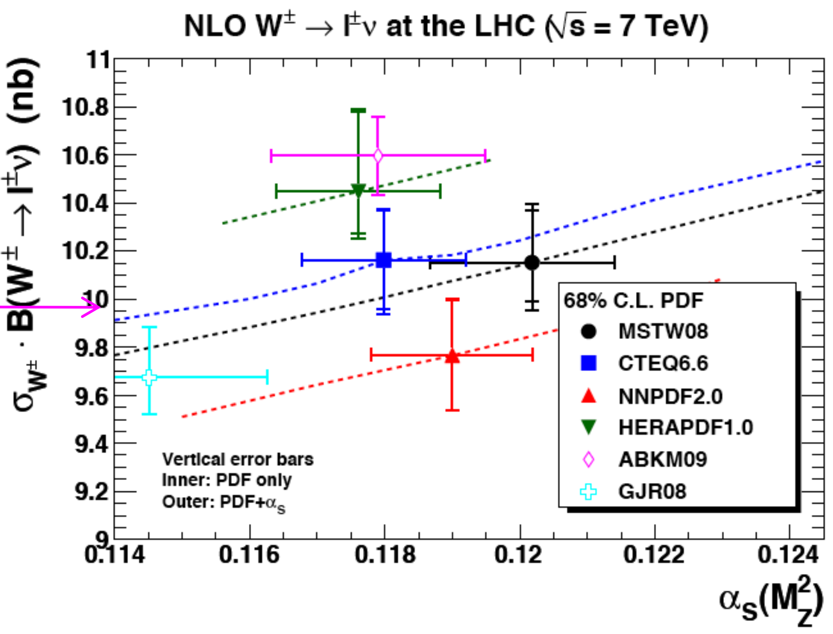
Aside: PDF4LHC benchmarking

- See https://wiki.terascale.de/index.php?title=PDF4LHC_WIKI

arXiv:1101.0536

- Look at PDF luminosities from different groups and predictions/ratios for cross sections (from G. Watt)
- CTEQ/MSTW predictions for W cross section/uncertainty in very good agreement
    - small impact from different α_s value
    - similar uncertainty bands
- NNPDF prediction low because of use of ZM-VFNS
- HERAPDF1.0 a bit high because of use of combined HERA dataset

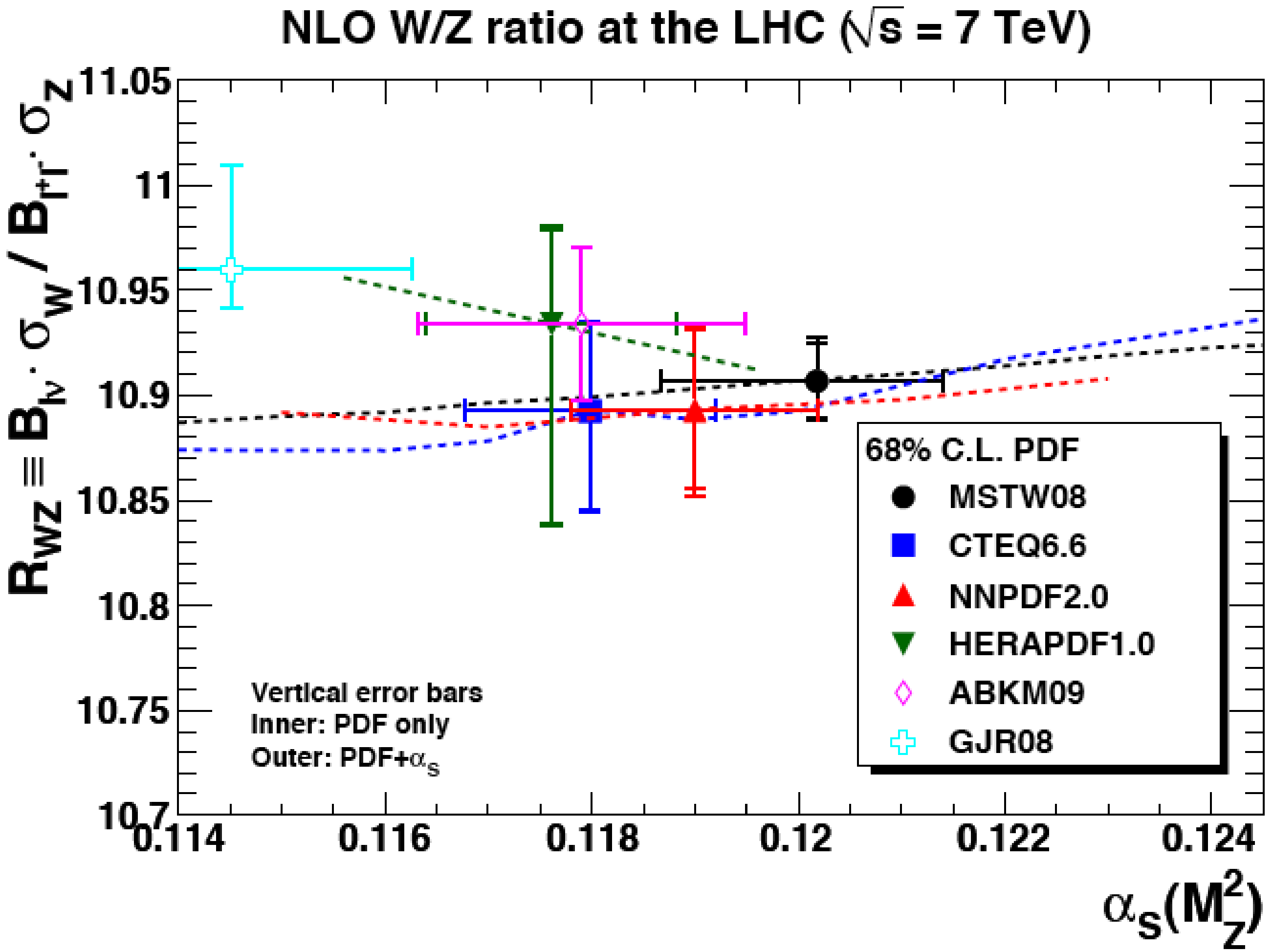




ATLAS

W/Z ratio

- Good agreement among the PDF groups
- Be a good test for ATLAS with higher statistics



The LHC ~~will be~~ is a very *jetty* place

- Total cross sections for tT and Higgs production saturated by tT (Higgs) + jet production for jet p_T values of order 10-20 GeV/c
- $\sigma_{\text{W+3 jets}} > \sigma_{\text{W+2 jets}}$

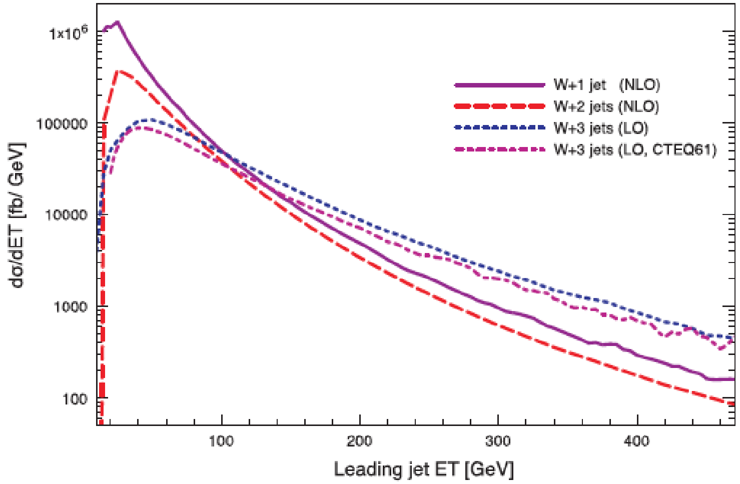


Figure 91. Predictions for the production of $W+ \geqslant 1, 2, 3$ jets at the LHC shown as a function of the transverse energy of the lead jet. A cut of 20 GeV has been placed on the other jets in the prediction.

- indication that can expect interesting events at LHC to contain many jets(especially from gg initial states)

14 TeV

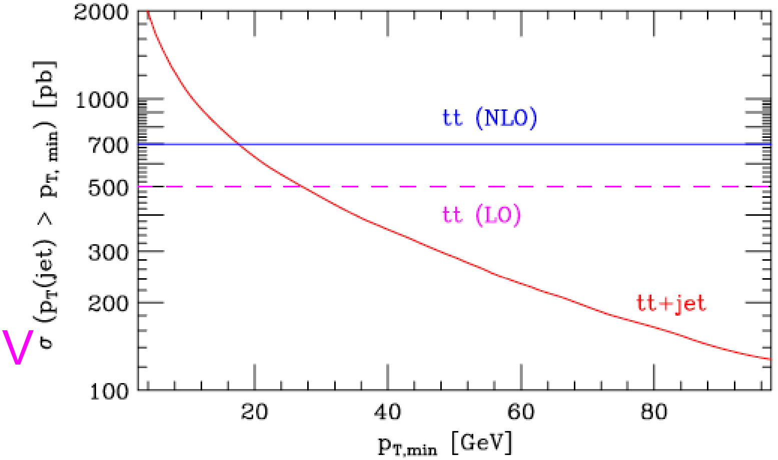


Figure 95. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

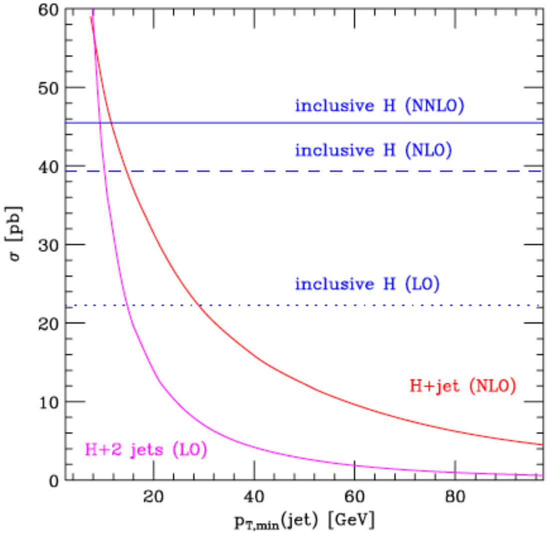
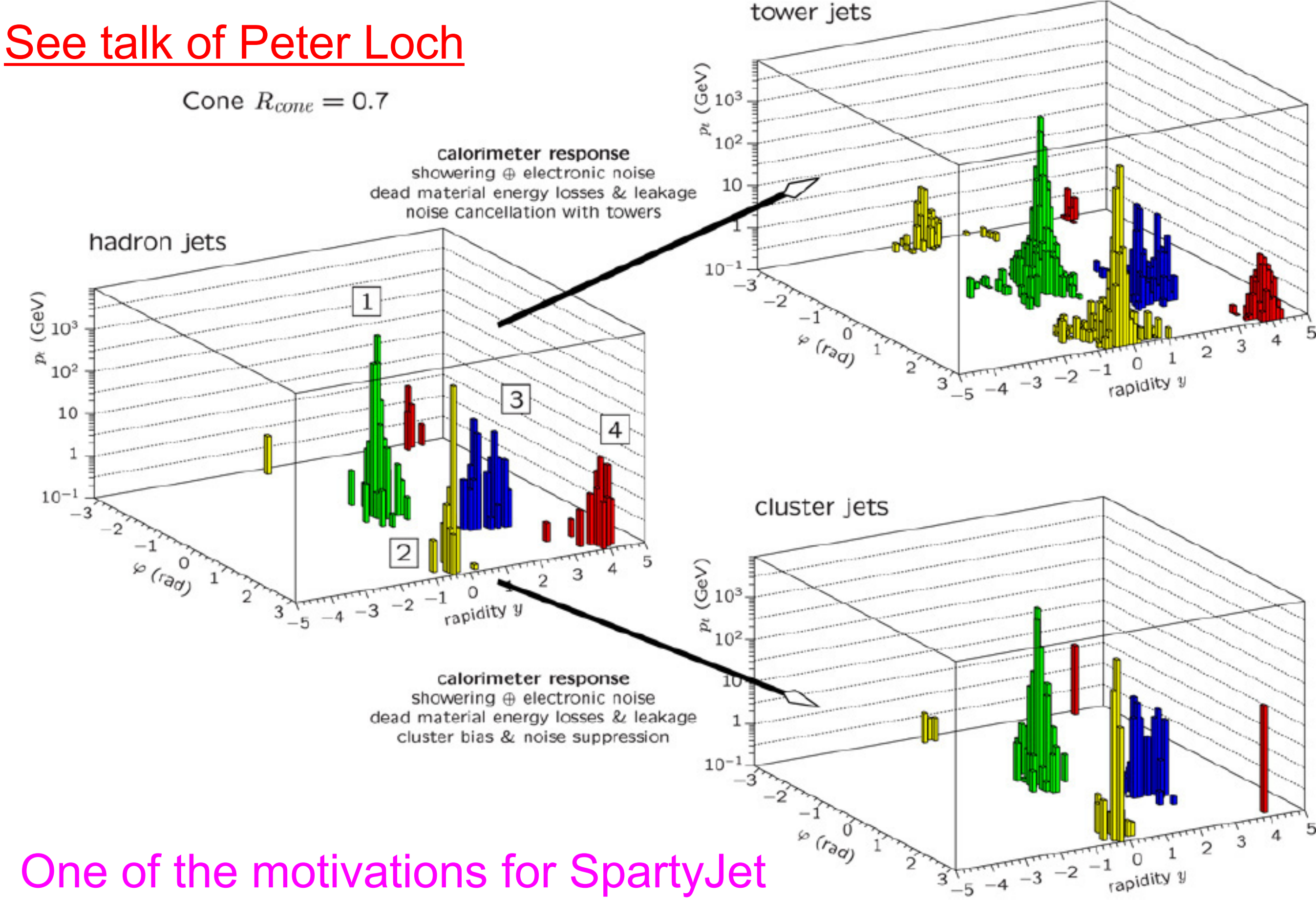


Figure 100. The dependence of the LO $t\bar{t}$+jet cross section on the jet-defining parameter $p_{T,\min}$, together with the top pair production cross sections at LO and NLO.

ATLAS jet reconstruction

- Using locally calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/parameters/jet substructure on every event

See talk of Peter Loch



blobs of energy in the calorimeter correspond to 1/few particles (photons, electrons, hadrons); can be corrected back to hadron level

rather than jet itself being corrected

similar to running at hadron level in Monte Carlos

One of the motivations for SpartyJet

Underlying event at the LHC

- Going into the LHC running, there was a fair amount of uncertainty as to the expected level of the underlying event
- Tunes existed for 630 GeV and 1.8/1.96 TeV, but energy extrapolation to 7 TeV depends on models
- Reminder: the UE includes BBR (beam-beam remnants)
    - soft
- …as well as multiple parton scatters
    - semi-hard
- Pythia (or any MC) regulates the dijet cross section adding in a p_T cutoff

$$\frac{1}{\hat{p}_T^4} \to \frac{1}{\left(\hat{p}_T^2 + \hat{p}_{To}^2\right)^2}$$

- For the Tevatron, p_{To}~2 GeV/c

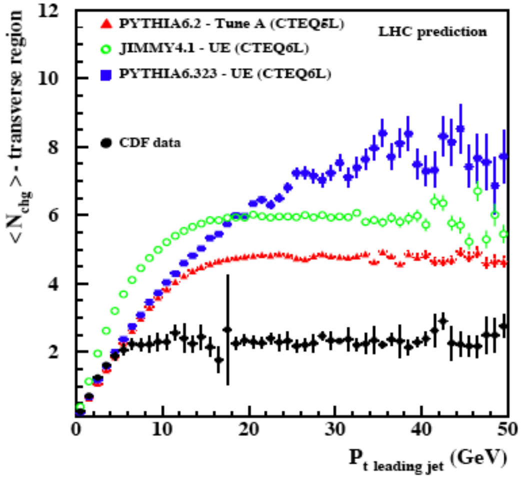
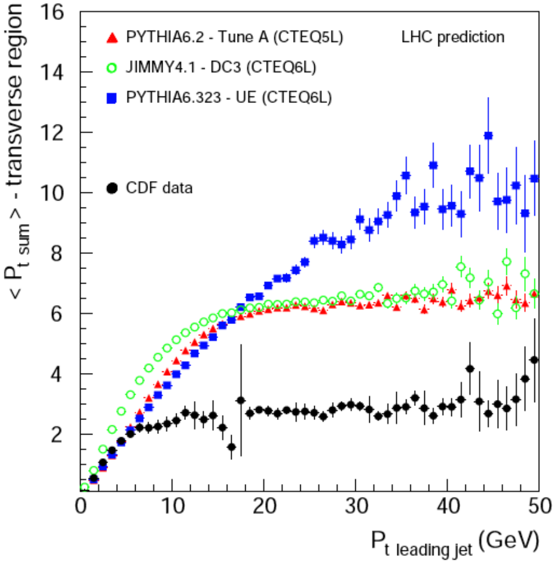
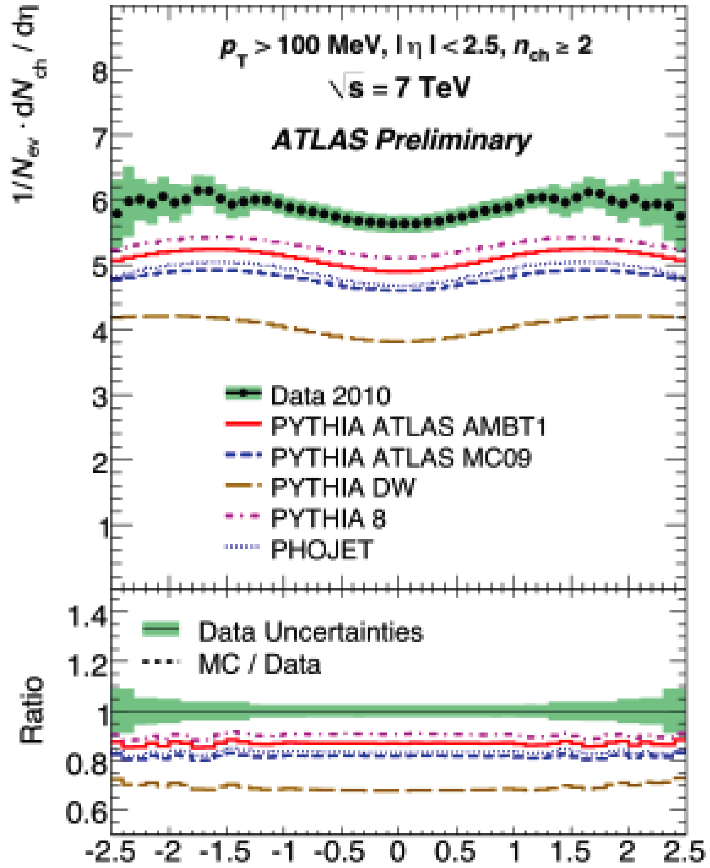


Figure 6: Pythia6.2 - Tune A, Jimmy4.1 - UE and Pythia6.323 - UE predictions for the average charged multiplicity in the underlying event for LHC pp collisions.

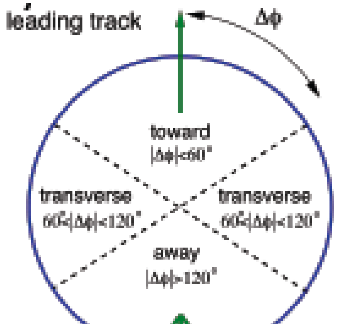


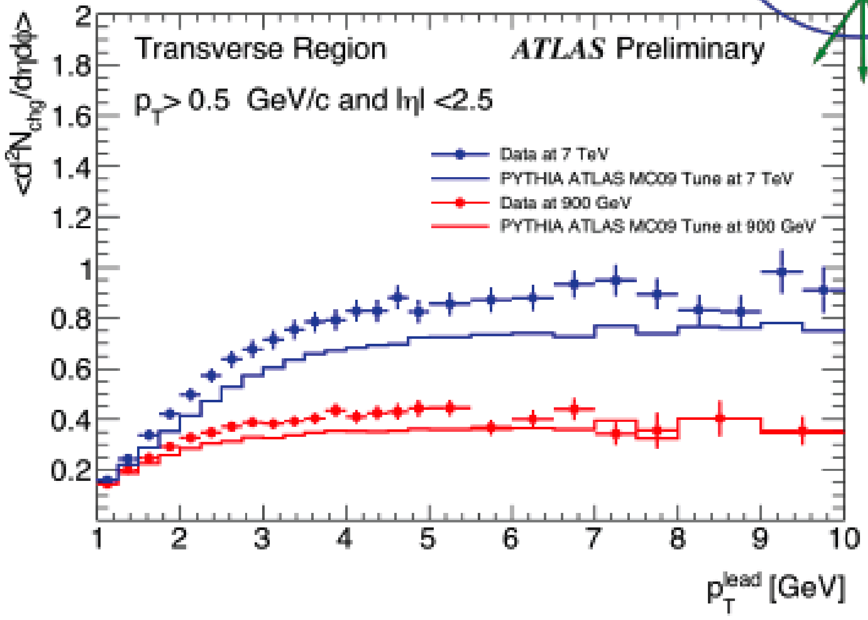
Underlying event measurements

- The UE affects almost every measurement at the LHC.
- Has to be determined by measurements within the kinematic acceptance of ATLAS and UE tunes for Monte Carlos adjusted to provide (as much as possible) a universal description of the UE at 7 TeV (as done at the Tevatron).
- Tunes used to provide an interface between parton and hadron levels.



These results contribute to new tunes of Monte Carlo programs



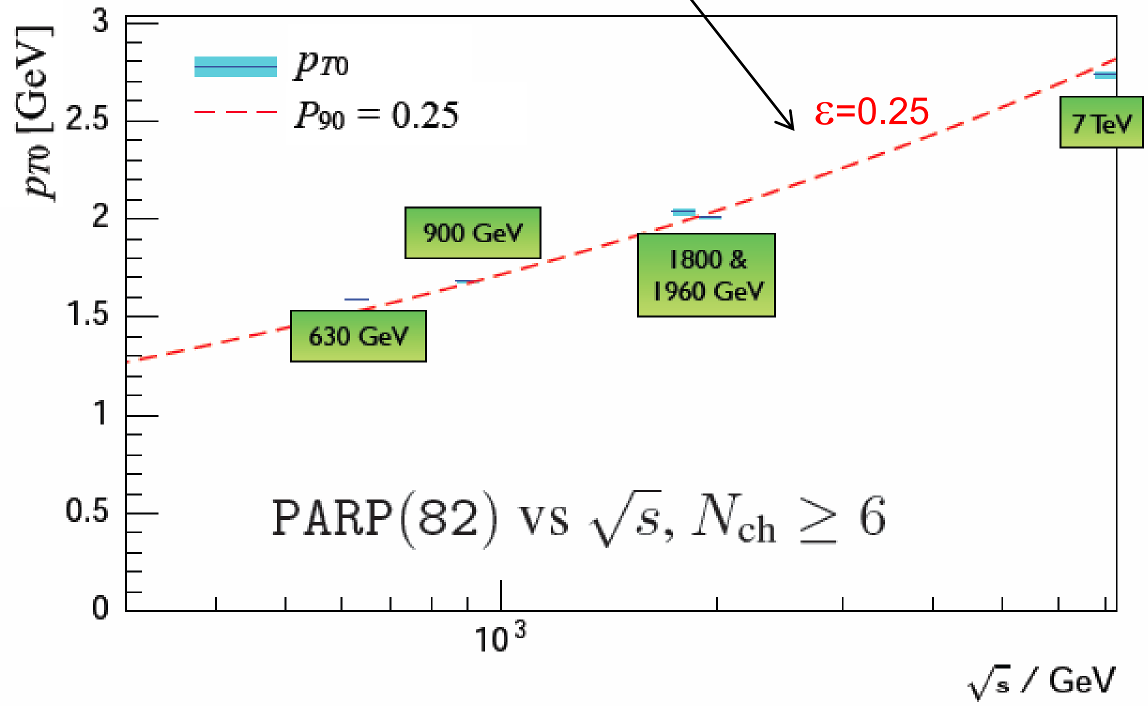


Underlying event at the LHC

The smaller the value of p_{To}, the more multiple scatters there are: the higher the value of p_{To}, the *jettier* the scatters are

Pythia model: $p_{To} = \left(\frac{E_{cm}}{E_o}\right)^{\varepsilon}$

Peter Skands
CTEQP-LPC workshop



cf., also, e.g., CMS, studies by R. Field

&

Sjöstrand & van Zijl, PRD36(1987)2019

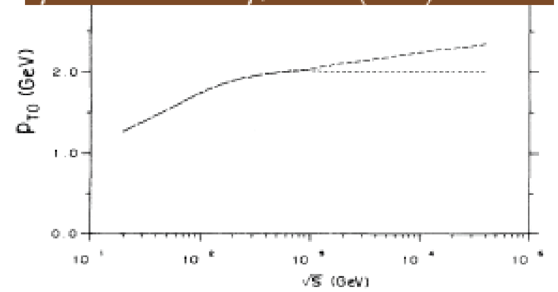


FIG. 8. Values for the cutoff parameter p_{T0} as a function of c.m. energy , as determined from comparisons with the average charged multiplicity. Dashed line, with a logarithmic extrapolation to higher energies, Eq. (38); dotted line, if assumed constant above 900 GeV.

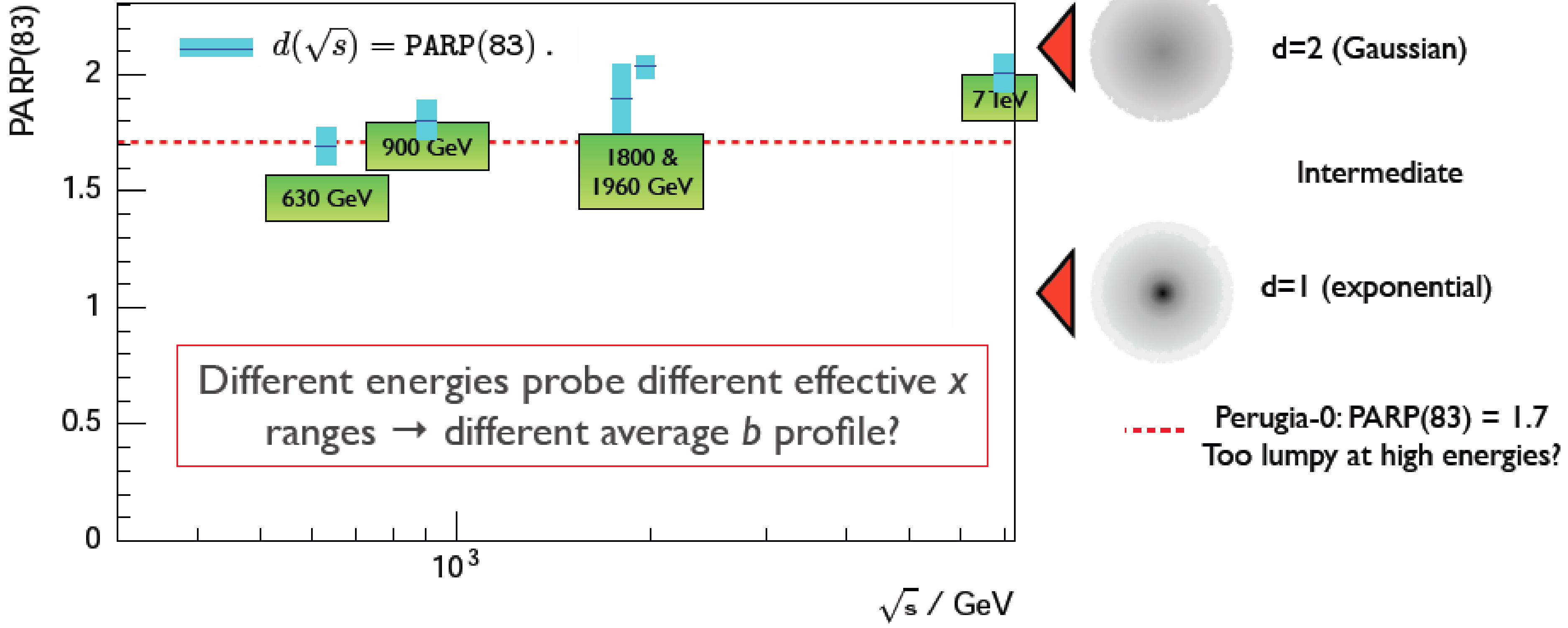
No large deviation from the assumed functional form

(E.g., Tunes A, DW, Perugia-0 use Exp = PARP(90) = 0.25)

Distributions inside proton

Peter Skands
CTEQP-LPC
workshop

Model : $\mathcal{O}(b) \propto \exp\left(-b^{d}\right)$ (independent of energy)



Different energies probe different effective *x* ranges → different average *b* profile?

Hint of departure from Gaussian (*d*=2) at lower E_{cm}?

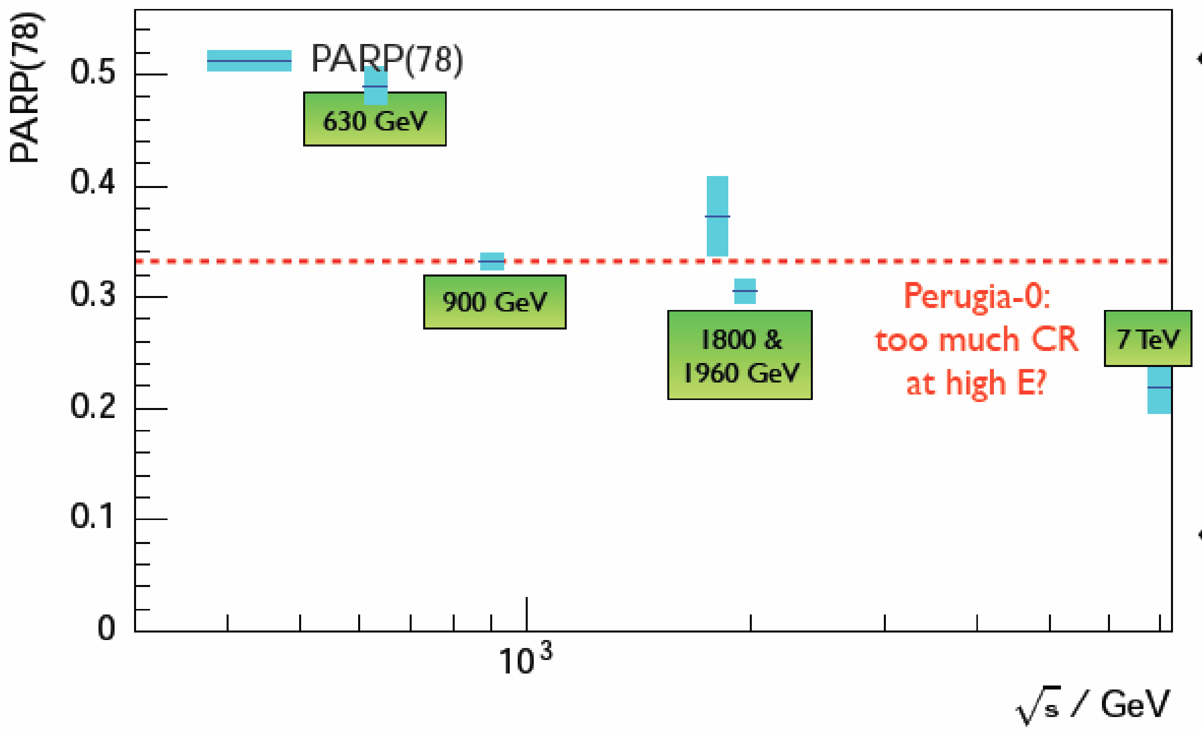
Interesting to get more independent handles on *b* distribution
+ make more use of 200 and 630 GeV data ?

Color string reconnections

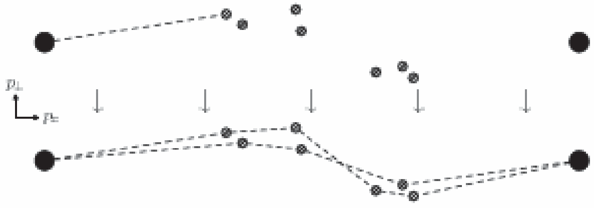
Peter Skands
CTEQP-LPC workshop

Model : $P_{keep} = (1 - P_{78})^{n_{int}}$

(energy dependence implicit through $\langle n_{int} \rangle$)



High CR
→ Short/Few Strings



Low CR
→ Long/Many Strings

Assumption of constant strength not supported by data!

Underscores the need for better physical understanding

What do we know…at this point?

- The behavior of the UE at the LHC is roughly what we expected
  - Pythia Tune DW, created from CDF UE studies, did a fairly good job in predicting behavior at 7 TeV
- But right now we have no model that describes all features of MB collisions at 900 GeV and 7 TeV
  - ATLAS Tune AMBT1 does a fairly good job on “diffraction-suppressed MB”
  - it’s easier to describe charged track properties for p_T>0.5 GeV/c than it is for extending down to p_T values of 100 MeV/c

- Rick Field; arXiv:1010.3558

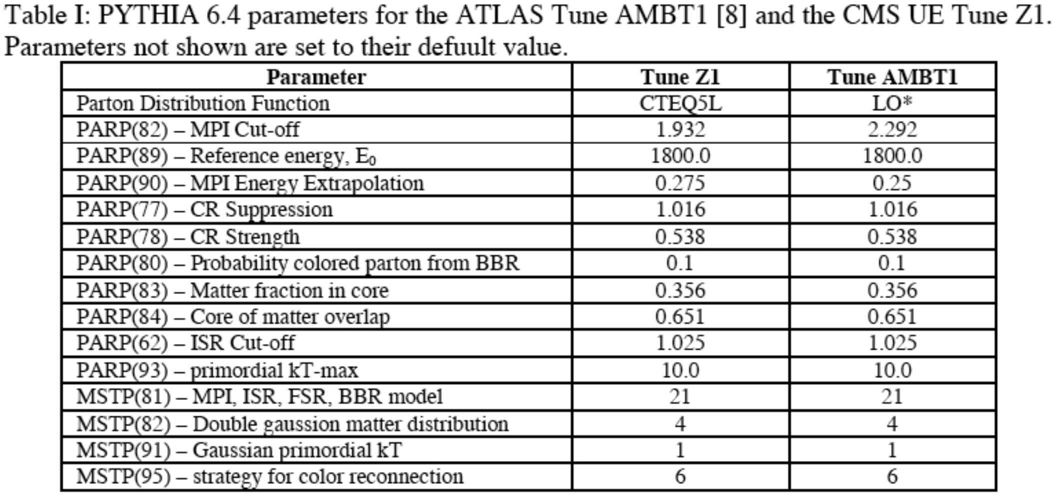


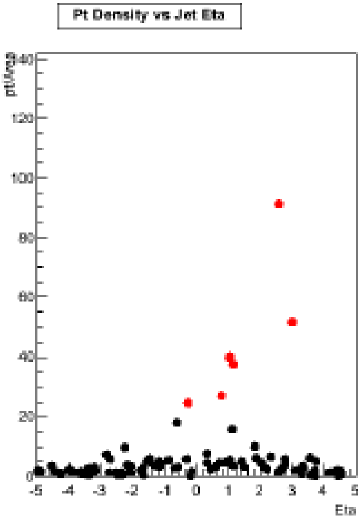
Table I: PYTHIA 6.4 parameters for the ATLAS Tune AMBT1 [8] and the CMS UE Tune Z1. Parameters not shown are set to their defuult value.

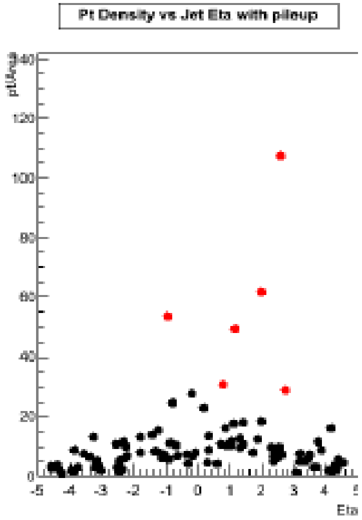
Parameter	Tune Z1	Tune AMBT1
Parton Distribution Function	CTEQ5L	LO*
PARP(82) – MPI Cut-off	1.932	2.292
PARP(89) – Reference energy, E_0	1800.0	1800.0
PARP(90) – MPI Energy Extrapolation	0.275	0.25
PARP(77) – CR Suppression	1.016	1.016
PARP(78) – CR Strength	0.538	0.538
PARP(80) – Probability colored parton from BBR	0.1	0.1
PARP(83) – Matter fraction in core	0.356	0.356
PARP(84) – Core of matter overlap	0.651	0.651
PARP(62) – ISR Cut-off	1.025	1.025
PARP(93) – primordial kT-max	10.0	10.0
MSTP(81) – MPI, ISR, FSR, BBR model	21	21
MSTP(82) – Double gaussion matter distribution	4	4
MSTP(91) – Gaussian primordial kT	1	1
MSTP(95) – strategy for color reconnection	6	6

Area-based correction: Cacciari/Salam/Soyez

1) Find low p_T jets in event. (< 10GeV) We use kT5jet.
2) From these, find average/median pT density of event ρ
3) Determine area A of signal jets
4) Subtract "pileup/UE"estimate

$$p_{Tcorr} = p_T - \rho A$$

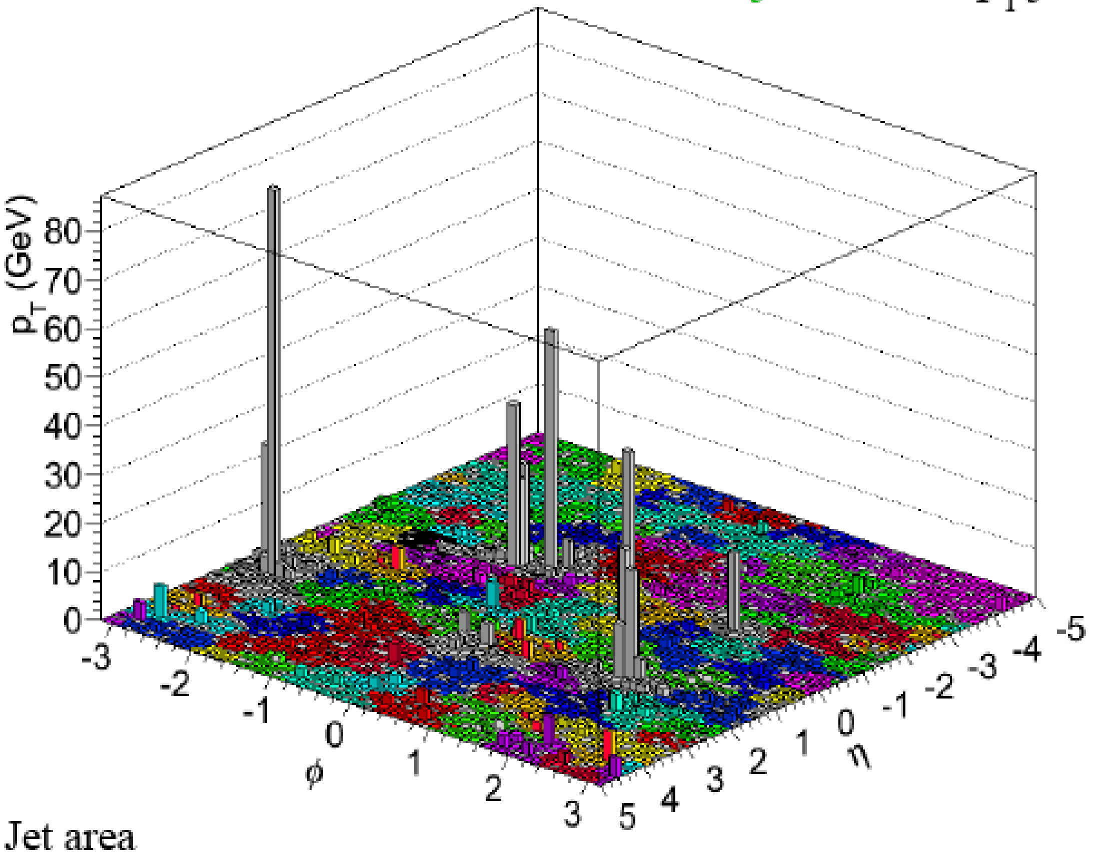

Pt Density vs Jet Eta


Pt Density vs Jet Eta with pileup

W+5j event with kT5Jets

Gray jets = Signal Jets

Colored jets = Low p_T jets



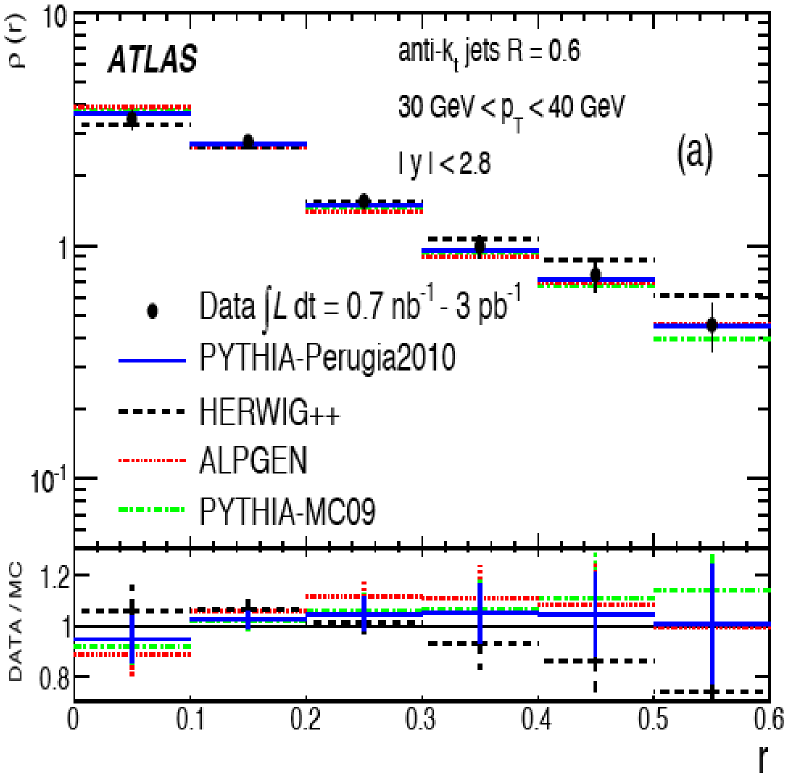
- Black points used to find pT density
- Red points are then corrected according to Jet area

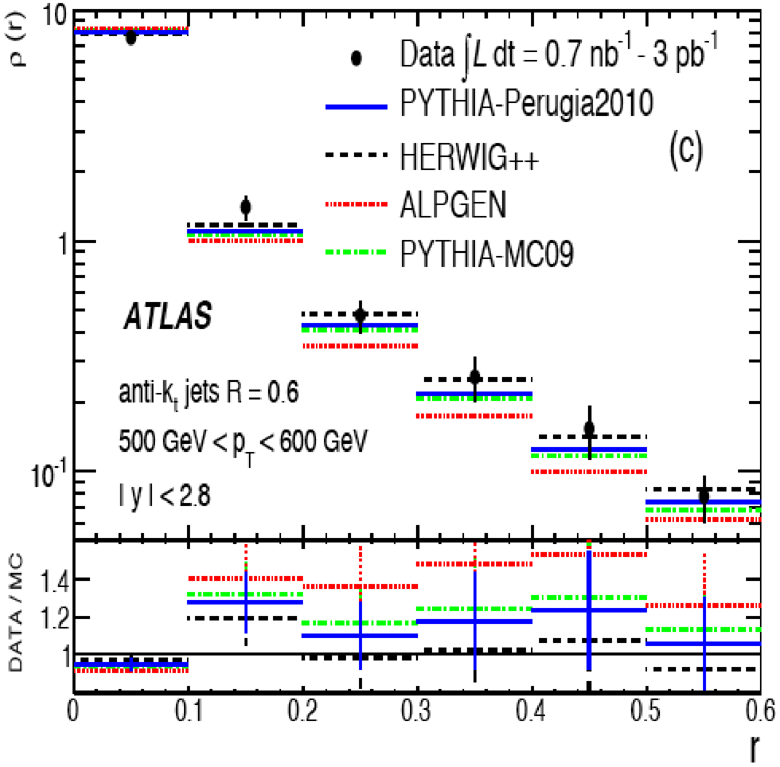
See talk of Brian Martin. Used in SpartyJet.

QCD engineering: jet shapes

- Validates energy scale corrections and parton shower modelling
- Key input to future jet cross section corrections
- Jet shape (at least at low p_T) depends on correct tune to underlying event, soft radiation and hadronization, in addition to good description of perturbative physics

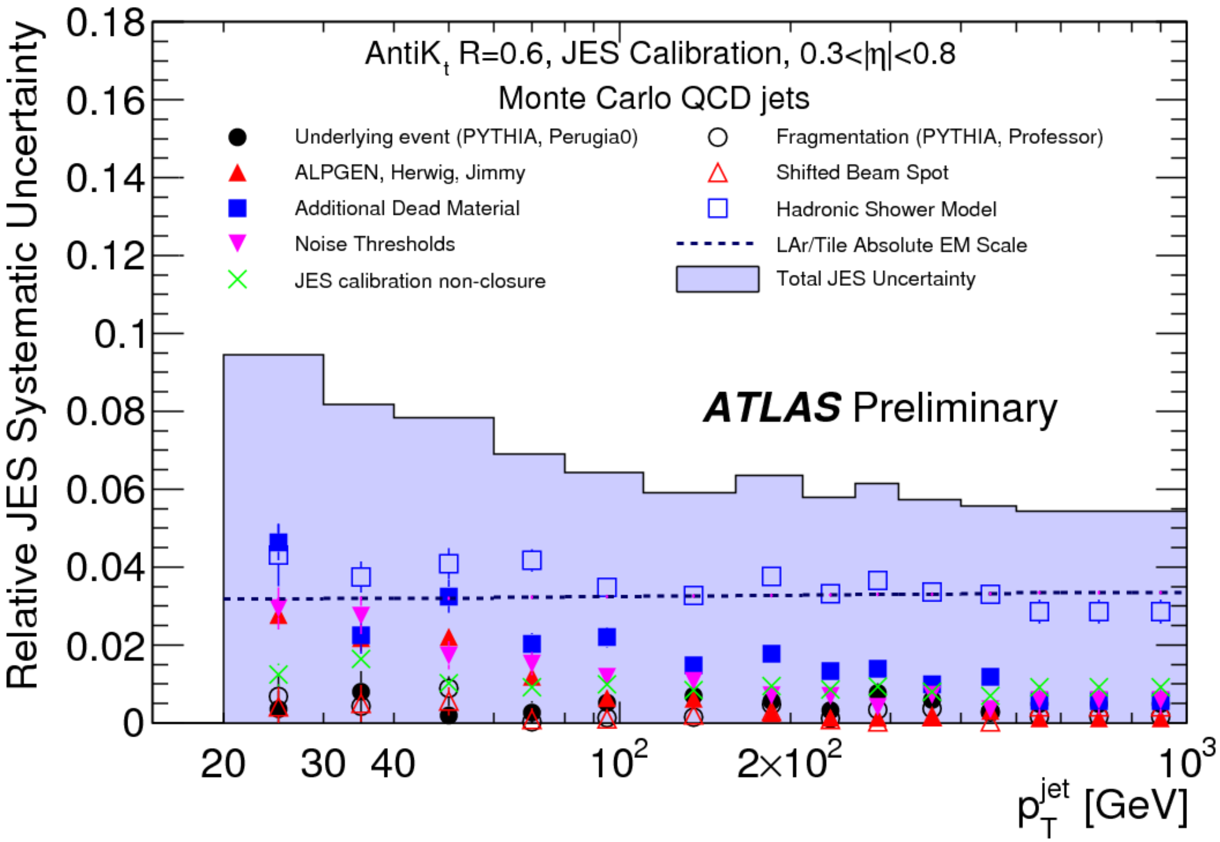
arXiv:1101.0070 (sub to PRD)





Jet Energy Scale (JES) uncertainty

- Dominant uncertainty in jet cross section measurements
- Right now are using a very conservative estimate
- Will improve (soon) as we get more data/more understanding
- See ATLAS-CONF-2010-056

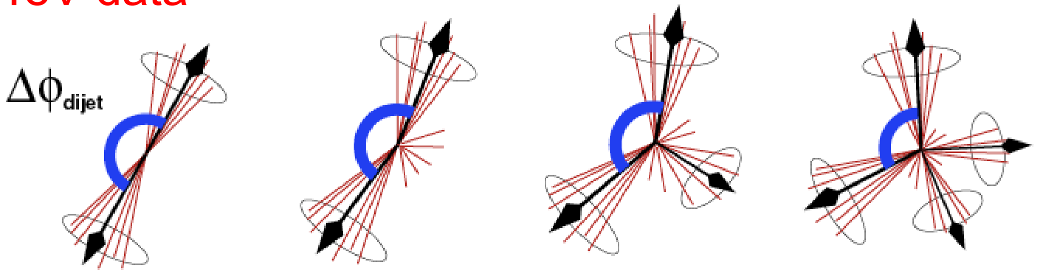


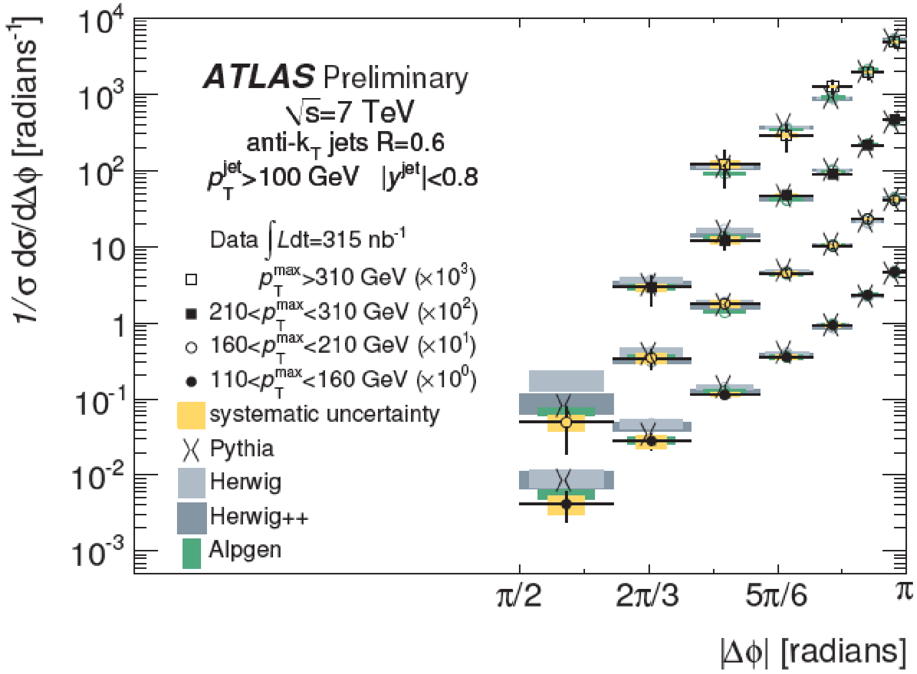
7-10% energy uncertainty in ATLAS results (6-9% for R=0.4)

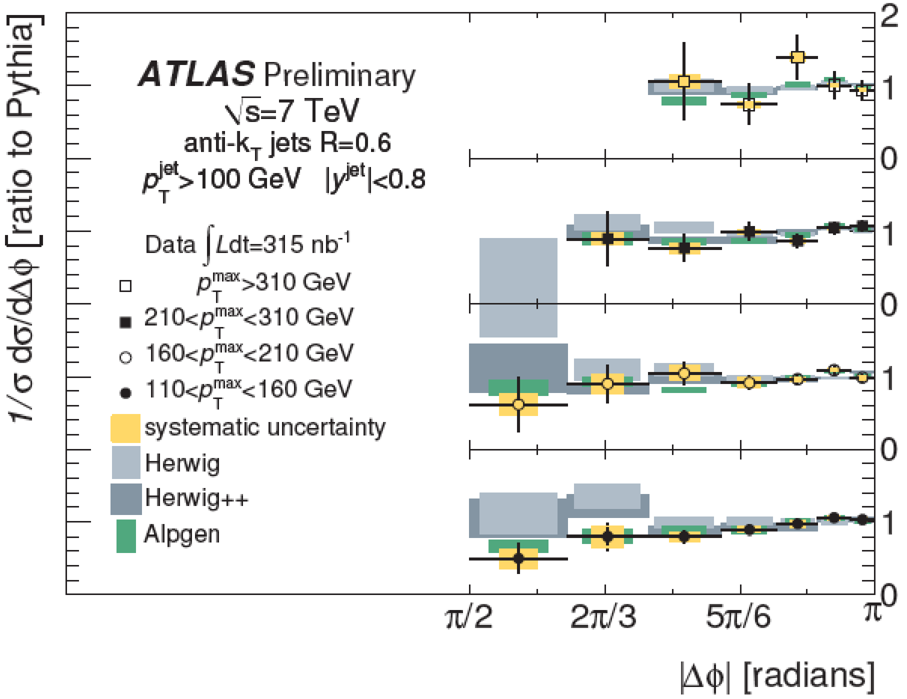
(Not corrected for pileup contributions)

Dijet decorrelation

Dijet decorrelation resulting from both hard and soft gluon radiation: tests level of agreement of matrix element + parton shower calculations with 7 TeV data



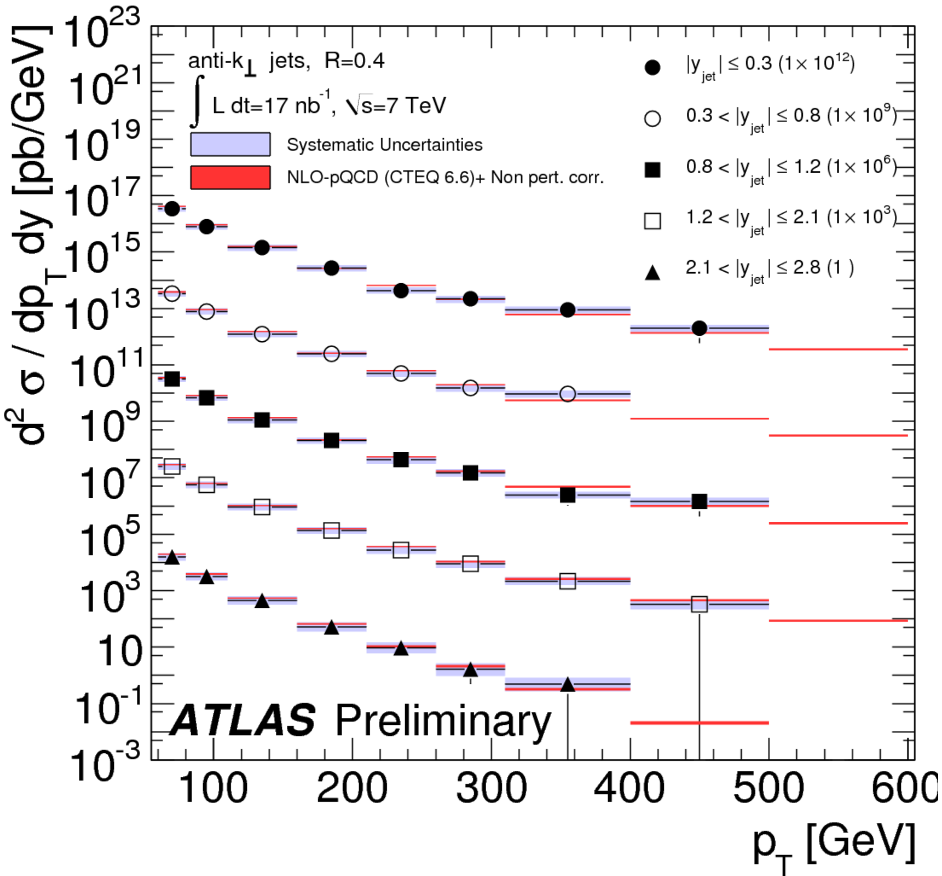


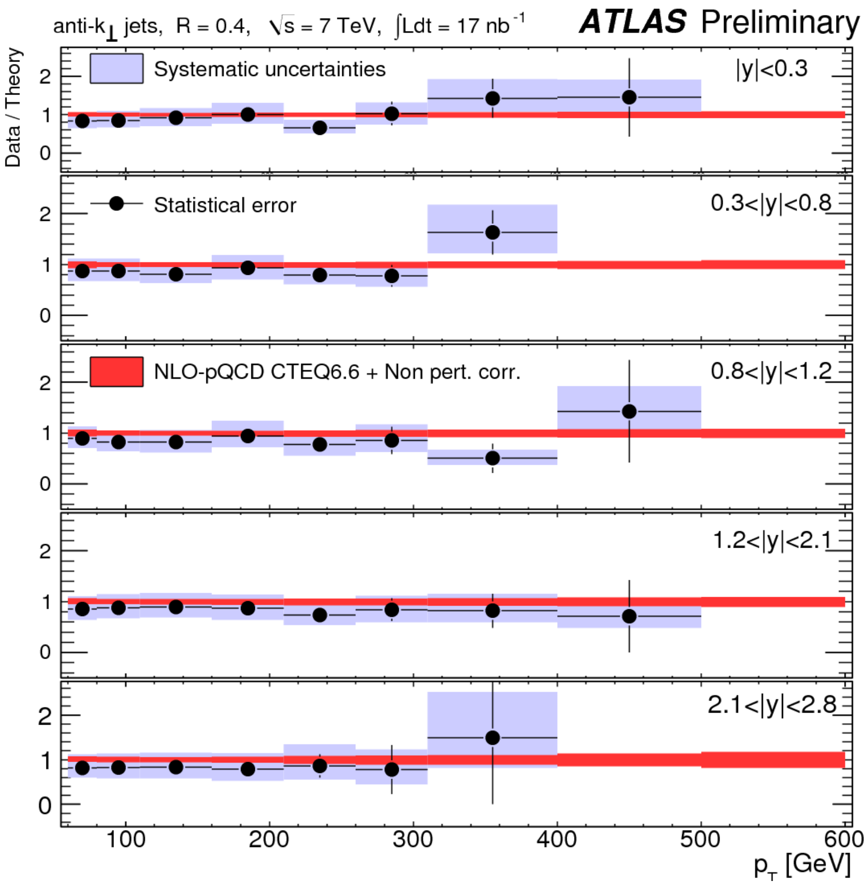


Inclusive jet production R=0.4

- Antikt jet algorithm used: correct jet cross sections to particle level
- Non-perturbative corrections applied to NLO predictions (NLOJET++)
- Good agreement with NLO predictions using CTEQ6.6 PDFs (see ATLAS-CONF-2010-050)
- Good practice: use the name of the program and the scale choice

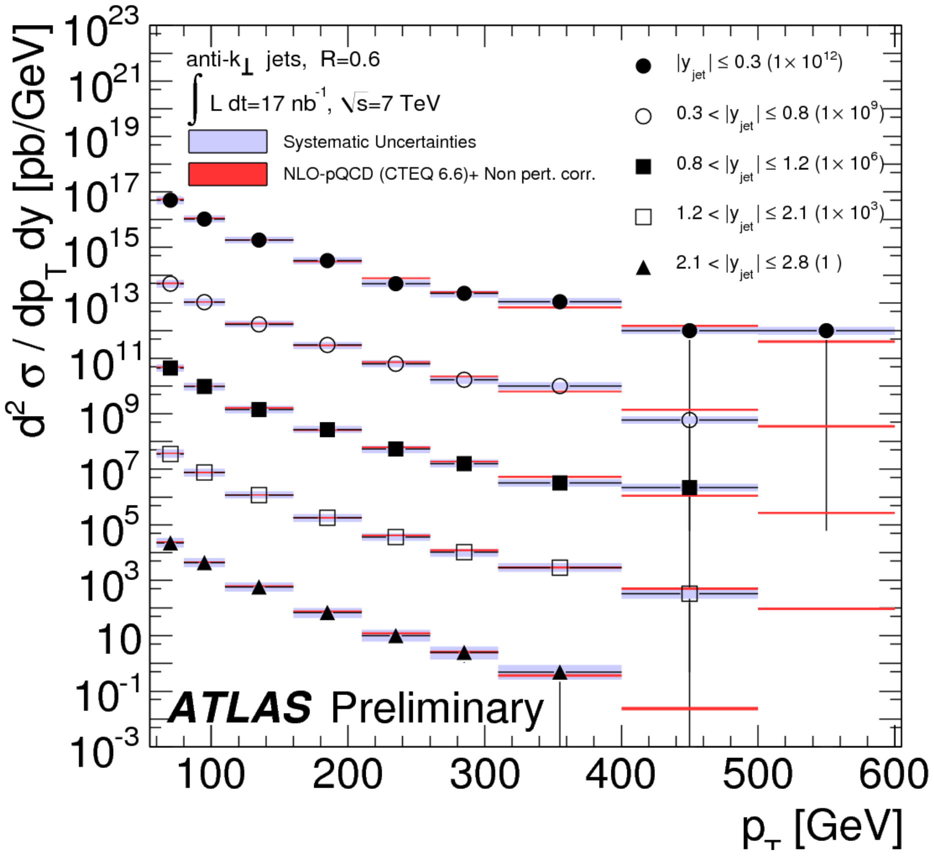
arXiv:1009.5908v2
(submitted to EPJC)

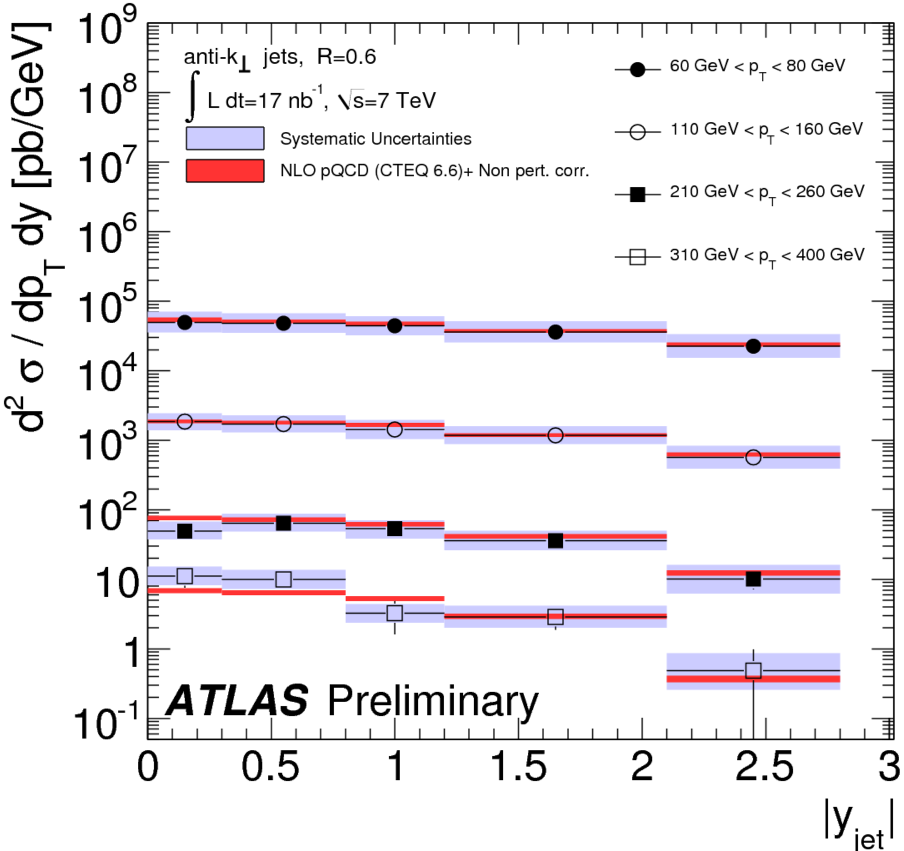




Inclusive jet production R=0.6

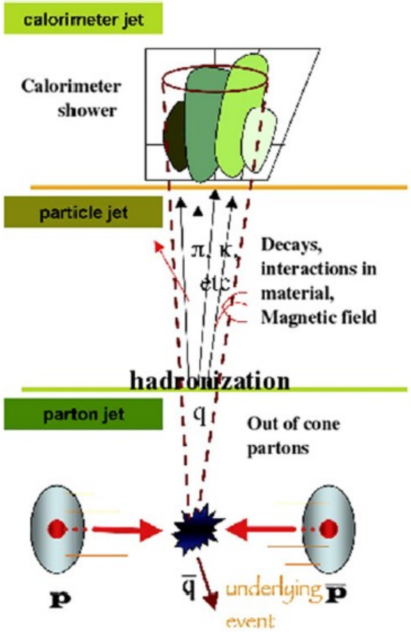
- Important to be able to measure jets with different parameters/algorithms
  - ATLAS uses primarily antikT4 and antikT6
- Not really done in the past in hadron-hadron colliders, but is a crucial part of the LHC physics program
- Different algorithms/parameters may illuminate different dynamics of events





Choosing jet size

- Experimentally
  - in complex final states, such as W + n jets, it is useful to have jet sizes smaller so as to be able to resolve the n jet structure
  - this can also reduce the impact of pileup/underlying event



- Theoretically
  - hadronization effects become larger as R decreases
    - more gluons near edge of jet that hadronize to (some) pions outside of jet cone
  - for small R, ln R perturbative terms can become noticeable
  - this restriction in the gluon phase space can affect the scale dependence, i.e. the scale uncertainty for an n-jet final state can depend on the jet size

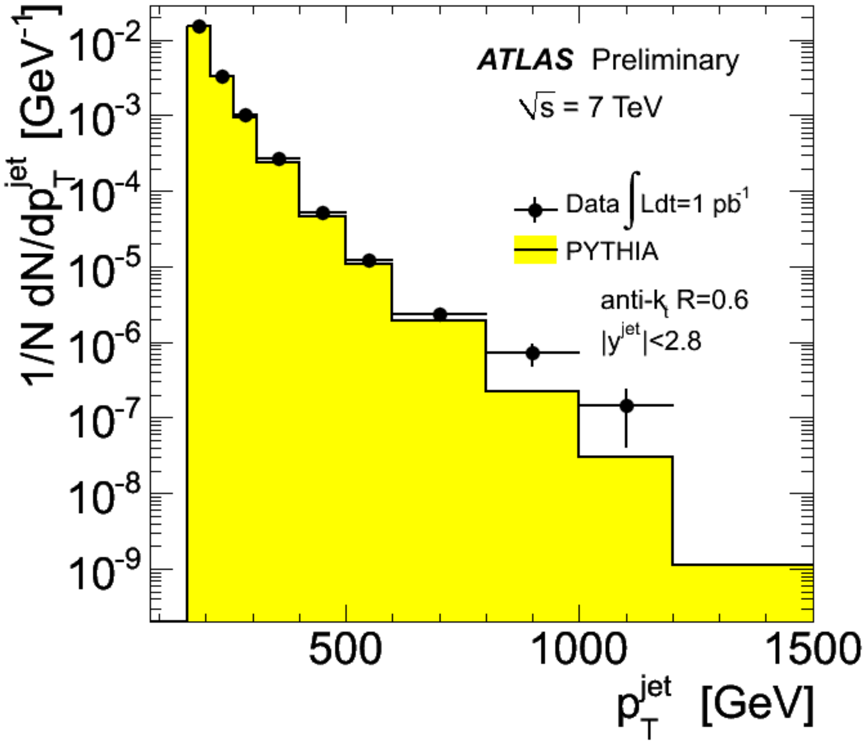
Another motivation for the use of multiple jet algorithms/parameters in LHC analyses.

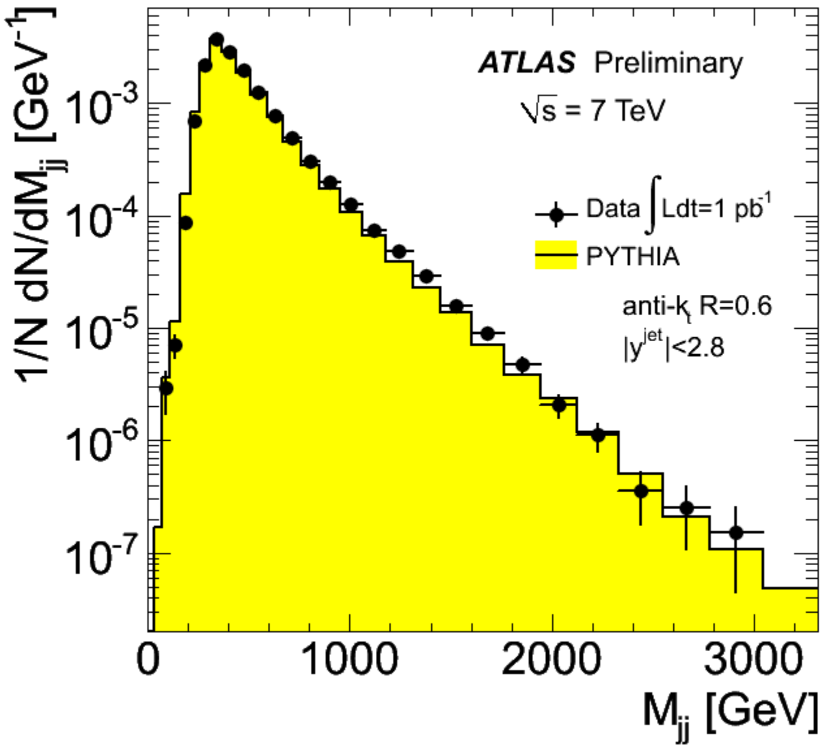
Jet sizes and scale uncertainties: the Goldilocks theorem

- Discussion at jet workshop in Seattle last year
- Take inclusive jet production at the LHC for transverse momenta of the order of 50 GeV
- Look at the theory uncertainty due to scale dependence as a function of jet size
- It appears to be a minimum for cone sizes of the order of 0.7
  - i.e. if you use a cone size of 0.4, there are residual un-cancelled virtual effects
  - if you use a cone size of 1.0, you are adding too much tree level information with its intrinsically larger scale uncertainty
- This effect becomes smaller for jet p_T values on the order of 100 GeV/c
  - how does it translate for multi-parton final states?

Some higher statistics results

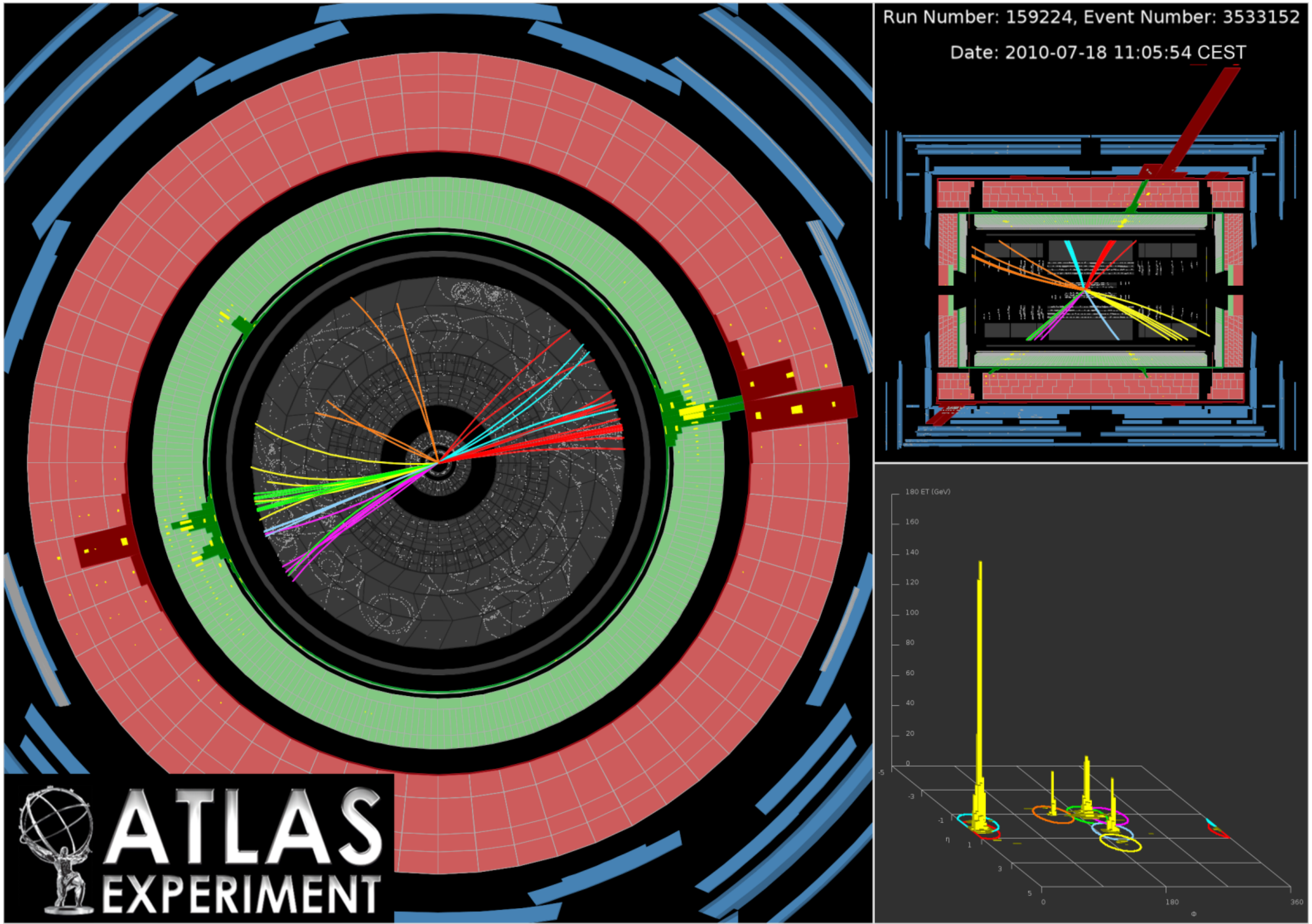
- Now have far exceeded kinematic reach of Tevatron
- Still relatively low x values though, compared to Tevatron's high p_T region
  - ◆ not so sensitive to high x gluon for example





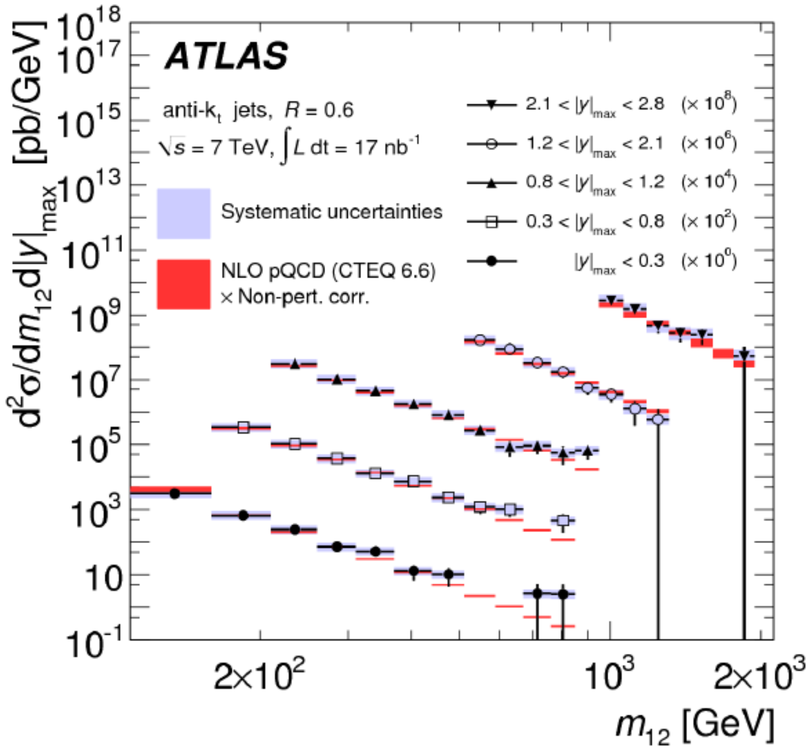
High p_T jet event

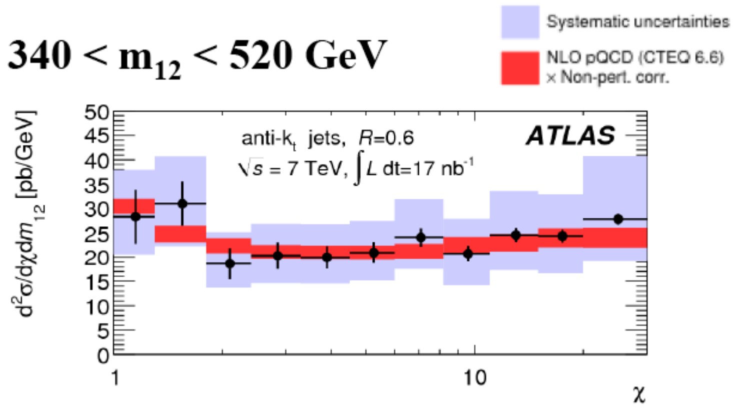
Lead jet has p_T of 1.12 TeV/c; 3 other high p_T jets in event; such multijet structure not uncommon in this high p_T (but still not high x) range



Dijets

- $p_T^{jet1(2)}$>60 (30 GeV); $|y_{jet}|$<2.8

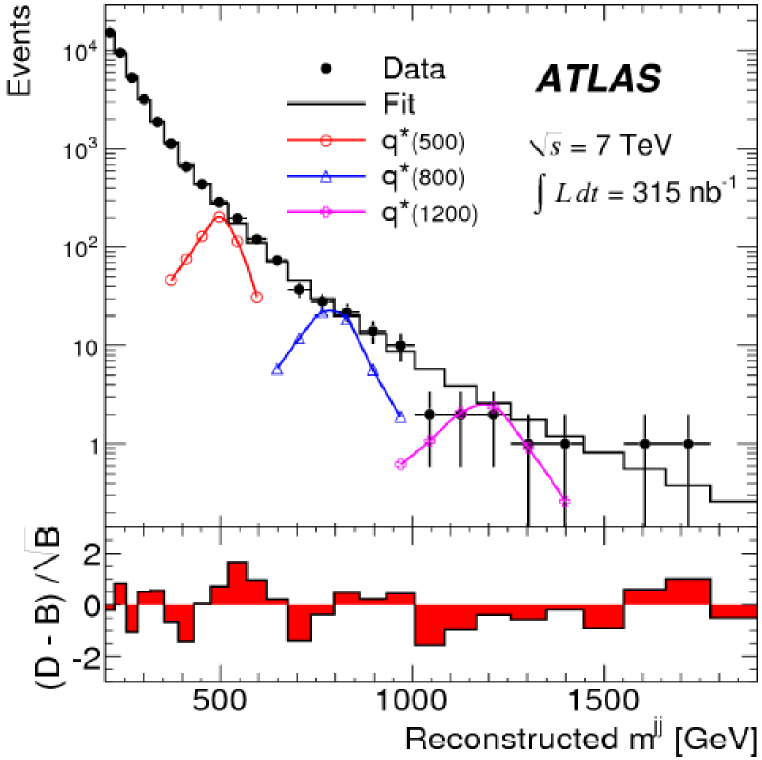


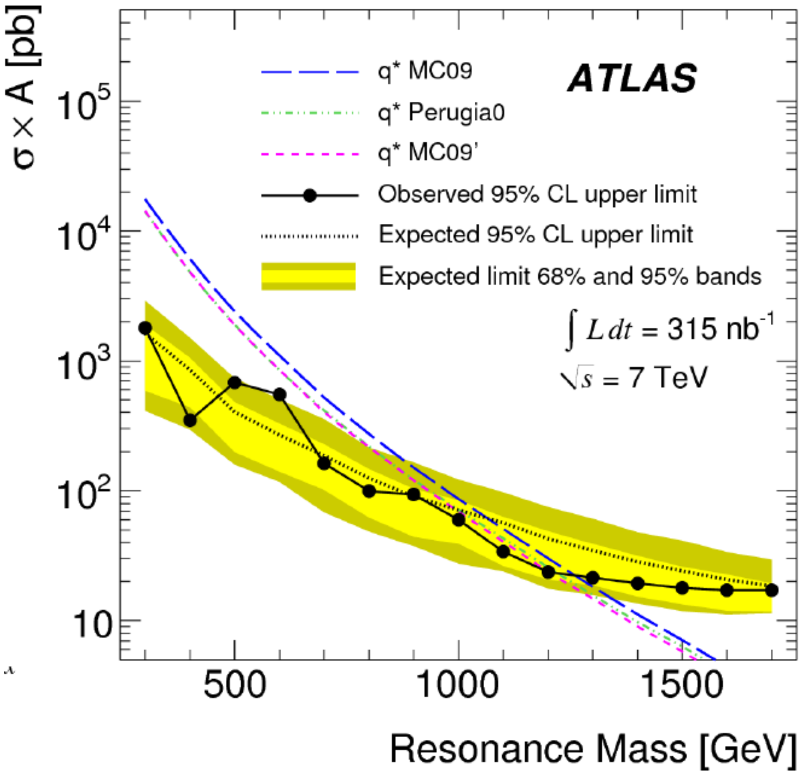


$$\chi = e^{\left|y_{jet\,1} - y_{jet\,2}\right|} = \frac{1+\cos\,\theta^*}{1-\cos\,\theta^*}$$

Dijets: TeV-scale resonances

- Searching for TeV-scale resonances with strong-couplings such as excited composite quarks, Randall-Sundrum gravitons, high mass gauge bosons, etc->fit to a smooth curve, look for bumps
- Assume conservative jet energy resolution uncertainty (σ/p_T~14%)
- Didn't find them (so far) arXiv:1008.2461 (Phys. Rev. Lett. 105, 161801(2010)
- First ATLAS result that overrode existing limit

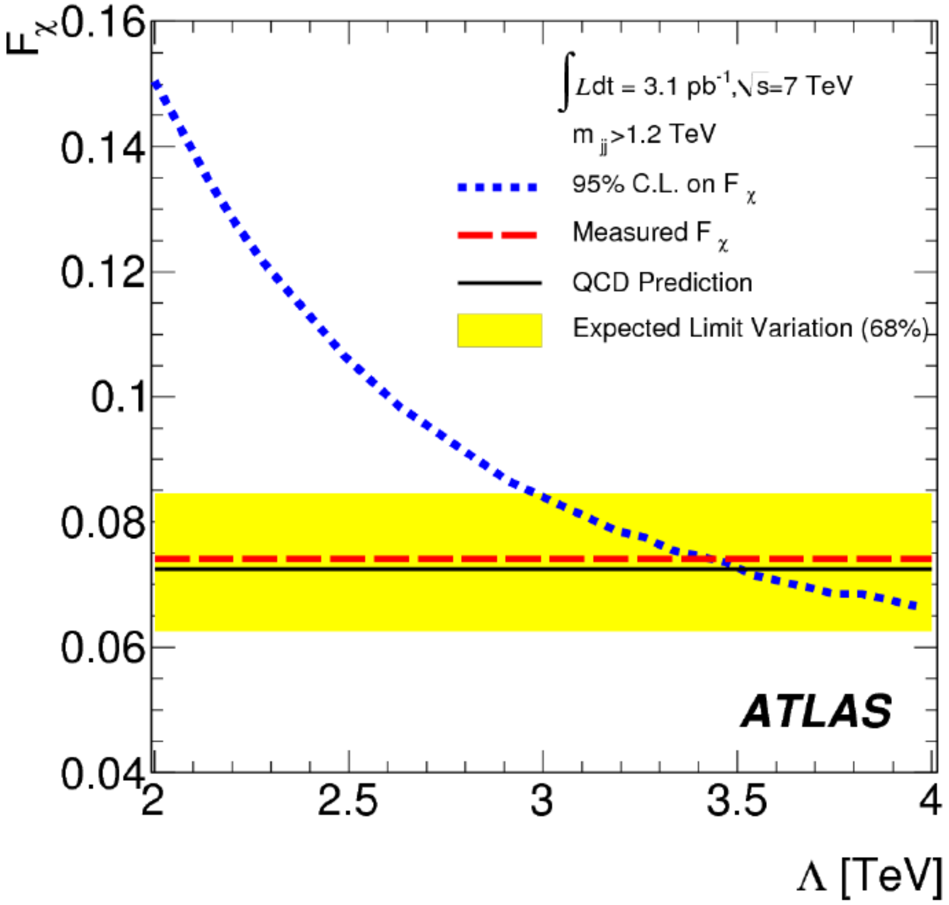


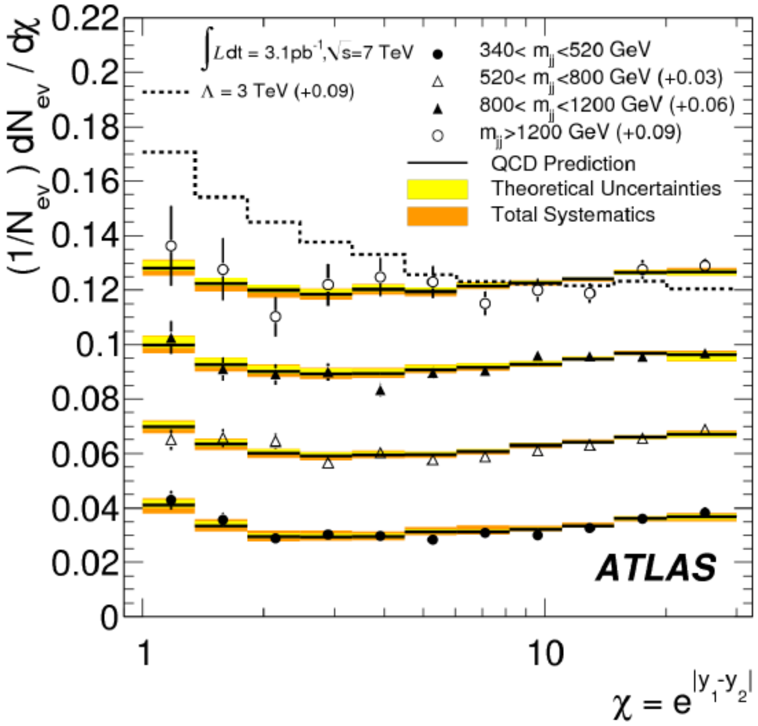


Non-resonant searches: contact interactions

- Λ>3.4 TeV @95% exclusion (new best limit)

arXiv:1009.5069 (submitted to PLB)





Aside: jet masses

- Very useful if looking for resonance in boosted jet (*top jet*)
- Naturally produced by QCD radiation
- Depends on jet algorithm/size

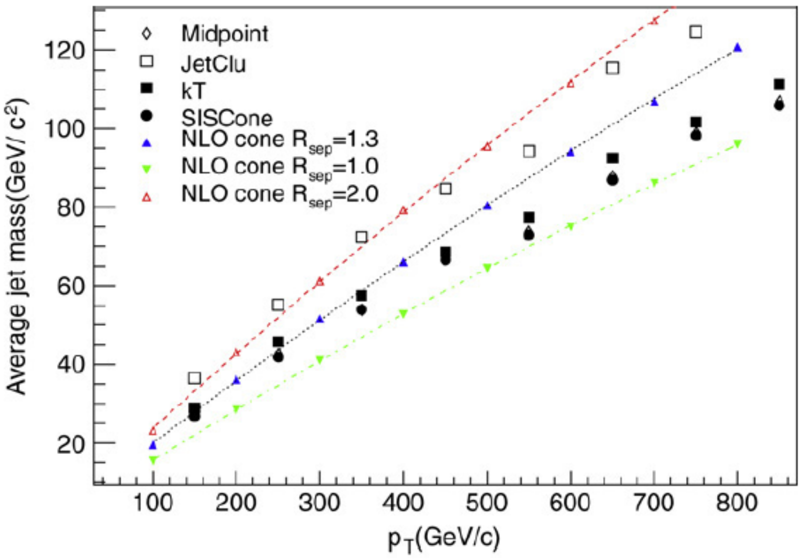


Fig. 53. The average jet mass is plotted versus the transverse momentum of the jet using several different jet algorithms with a distance scale ($D = R_{\text{cone}}$) of 0.7.

In NLO pert theory

phase space from pdf's

$$\sqrt{p_{J,\mu}p_J^{\mu}} = \sqrt{\langle M^2\rangle_{NLO}} = f\left(\frac{p_J}{\sqrt{s}}\right)\sqrt{\alpha_s(p_J)}\left(p_J R\right)$$

dimension

jet size

Rule-of-thumb

$$\sqrt{\langle M^2\rangle_{NLO}} \sim 0.2\, p_J R$$

…from Ellis et al review paper

Distribution of jet masses

- Sudakov suppression for low jet masses
- fall-off as $1/m^2$ due to hard gluon emission
- algorithm suppression at high masses
    - jet algorithms tend to split high mass jets in two

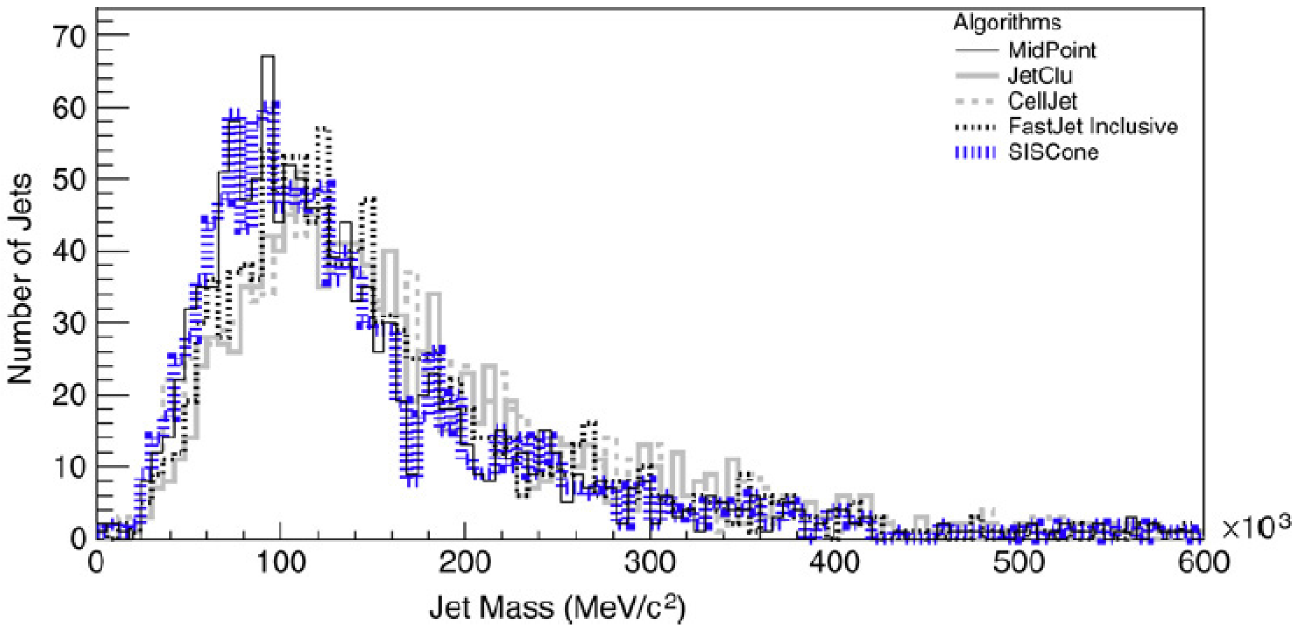
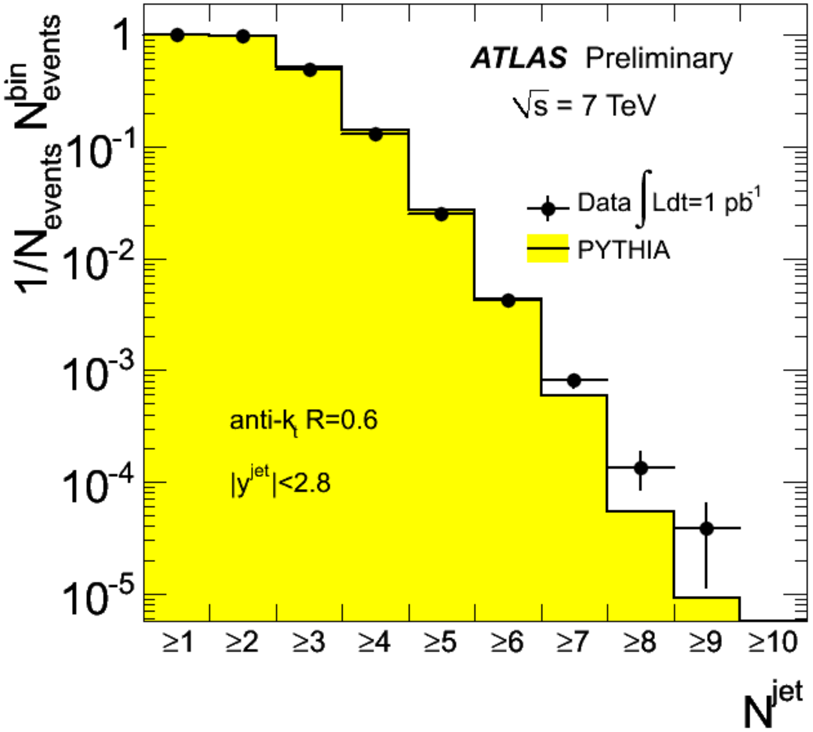


Fig. 51. The jet mass distributions for an inclusive jet sample generated for the LHC with a $p_{T,\min}$ value for the hard scattering of approximately 2 TeV/c, using several different jet algorithms with a distance scale ($D = R_{\text{cone}}$) of 0.7.

Multijets

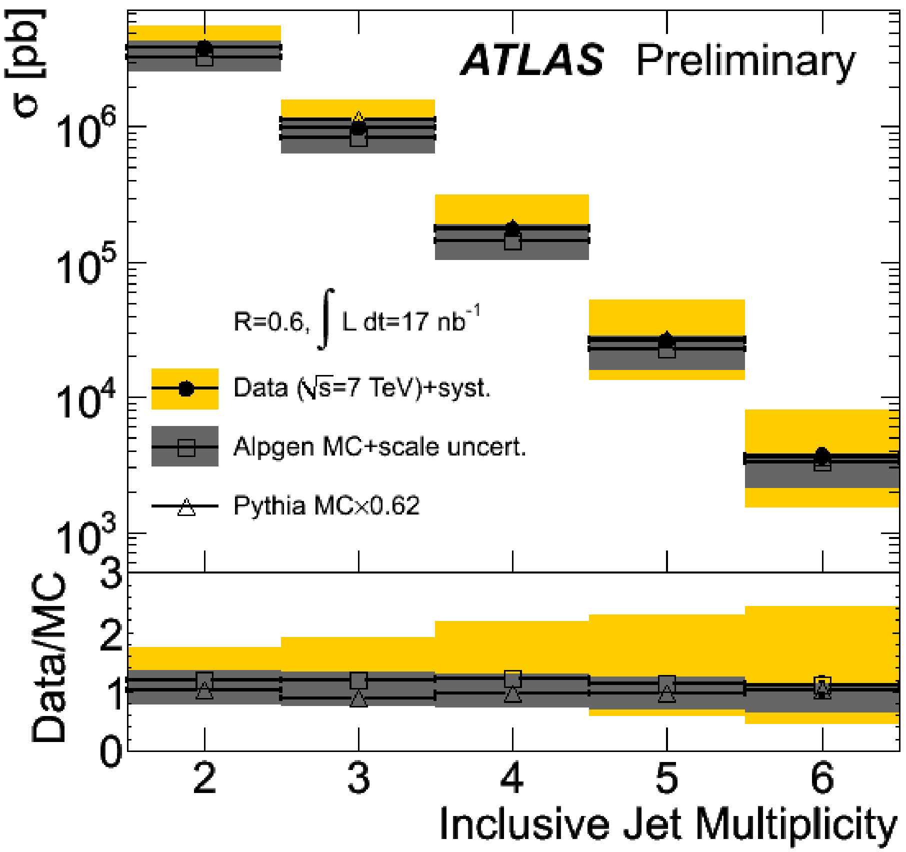
- Larger center-of-mass energy means that are able to routinely produce higher jet multiplicity events than at the Tevatron
  - p_T>30 GeV/c

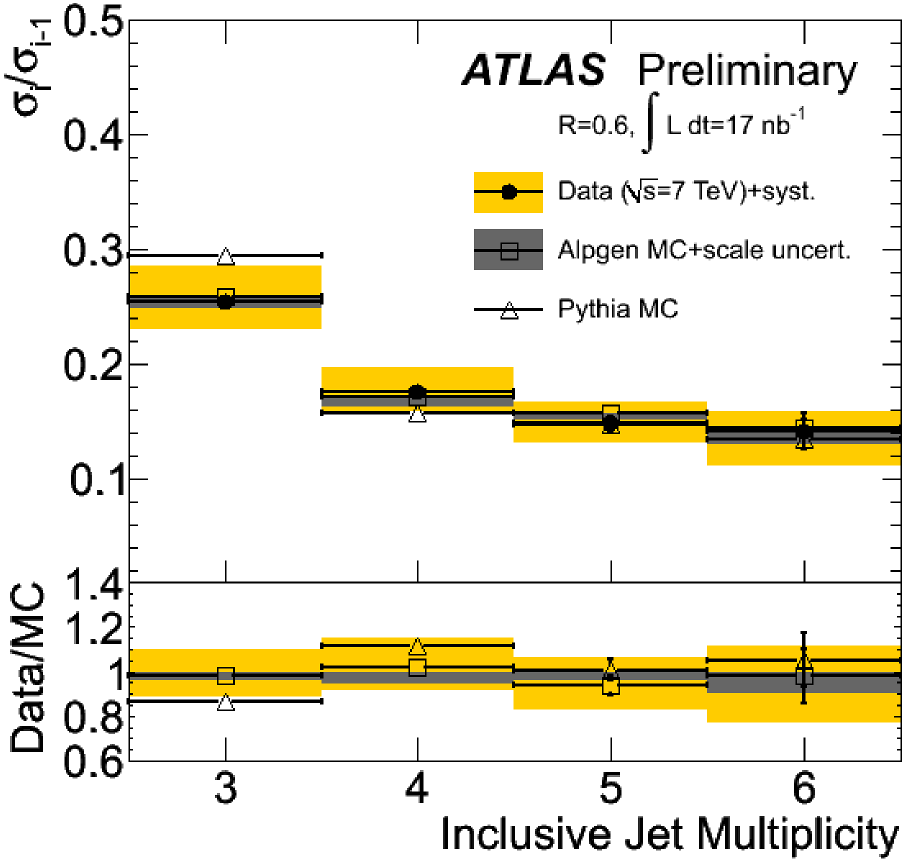


Multijets

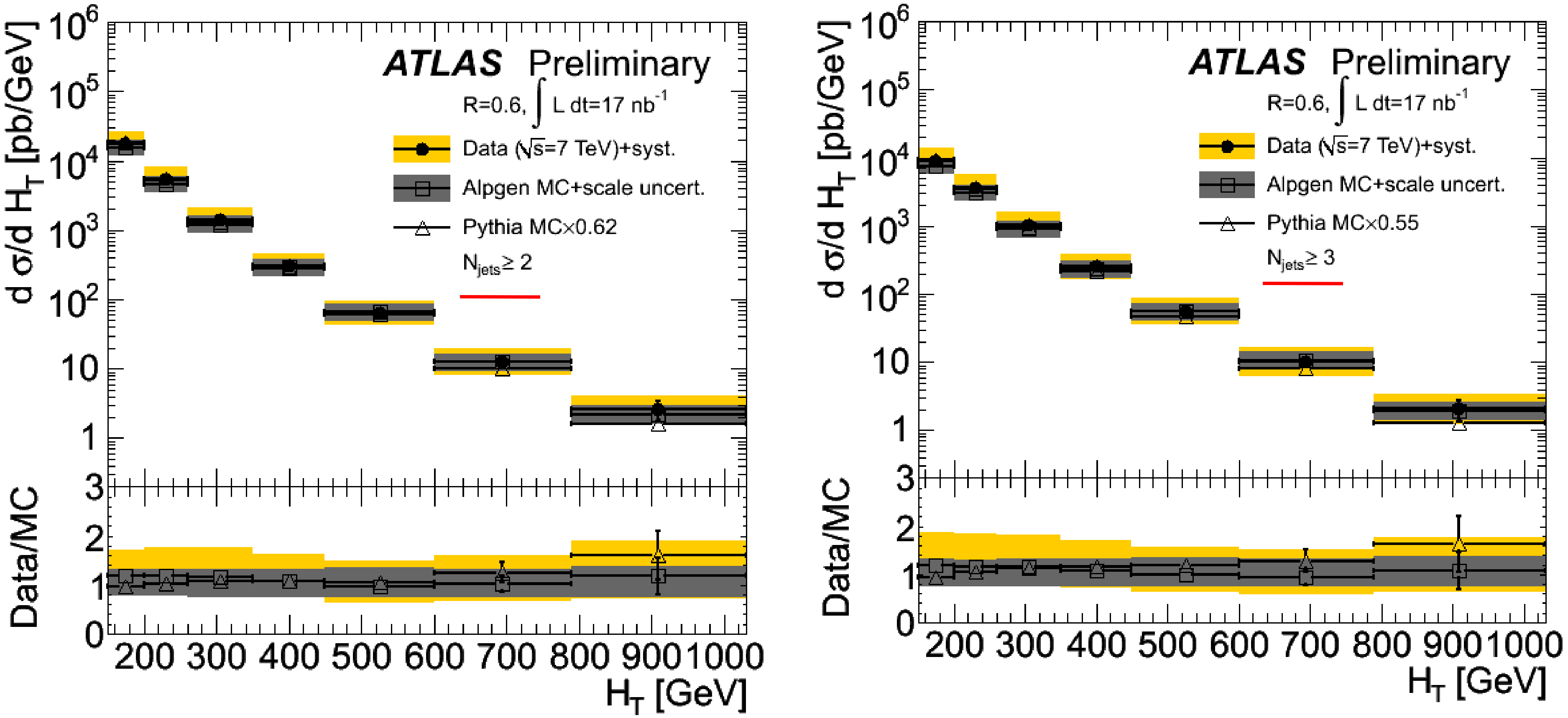
- Inclusive jet multiplicity distribution corrected to particle level compared to Alpgen and to Pythia
  - ◆ $p_T > 30$ GeV/c

•Ratio of n jet to n-1 jet cross section, corrected to particle level, and compared to Alpgen and to Pythia





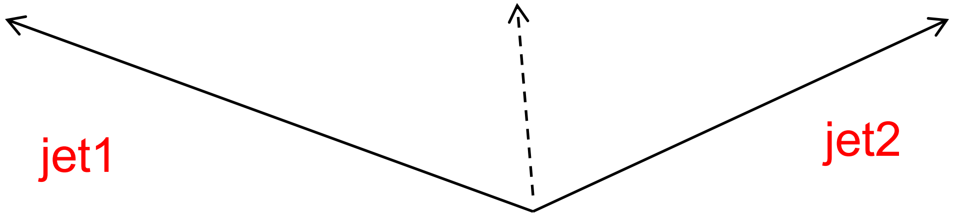
H_T distributions



H_T: sum of E_T of all objects in event

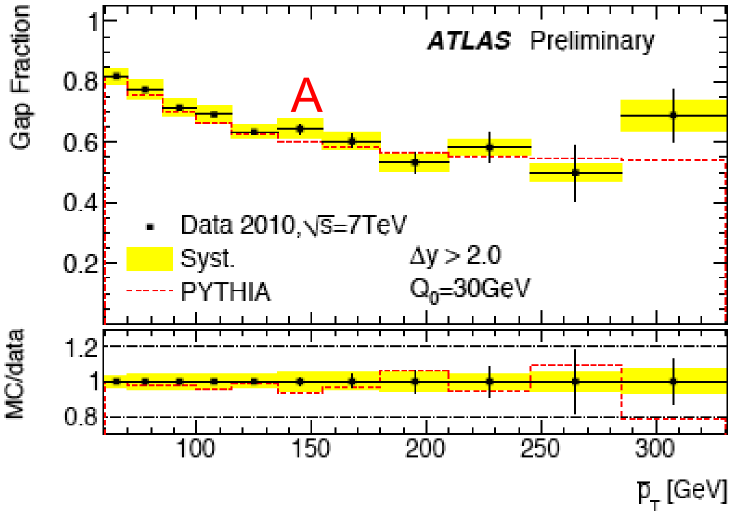
Gaps between jets

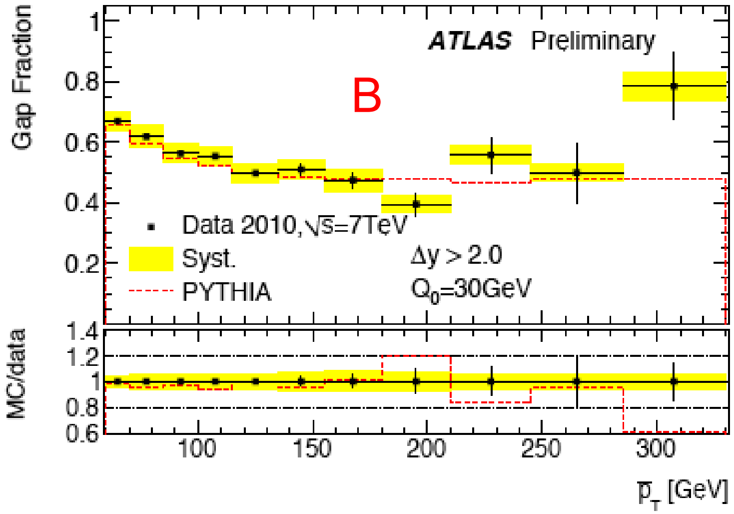
- Consider events with two jets separated by a rapidity interval Δy_{12}; the boundary jets



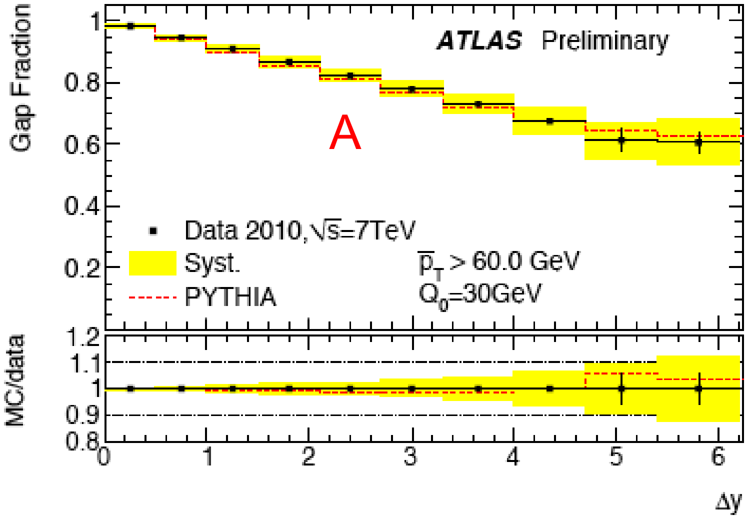
- Require each of the jets to have p_T>30 GeV, and that the average p_T of the two jets is 60 GeV
- Look at the probability for there to be no additional jets above a p_T of 30 GeV in the interval between these two boundary jets for two conditions:
  - A: the two jets are the two highest p_T jets in the event
  - B: the two jets have the largest value of Δy_{12}
- From DGLAP, expect rate for no jets in gap above 30 GeV to drop as (1) the p_T of the lead jet increases and (2) as the gap Δy_{12} increases
  - BFKL logs may also affect this rate
  - LHC is a good testing ground with its large kinematic reach

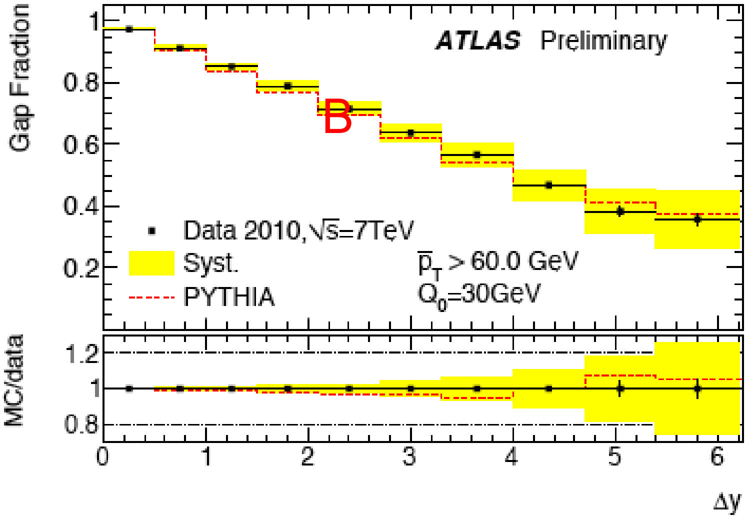
Gaps between jets





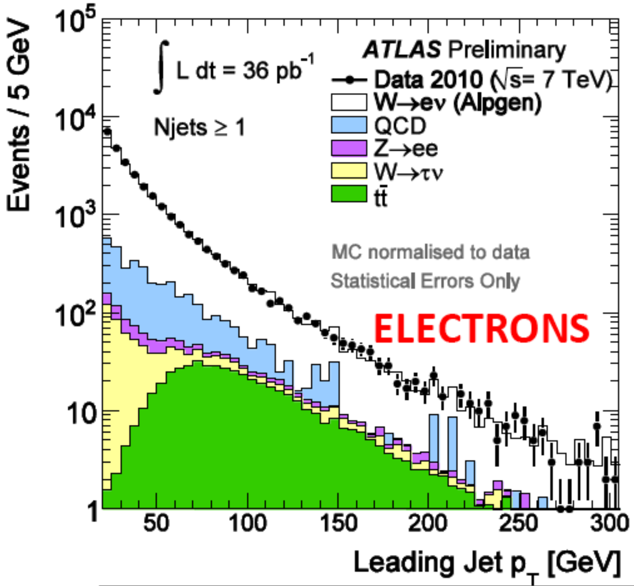
expected behavior observed; Pythia seems to work well (so far)

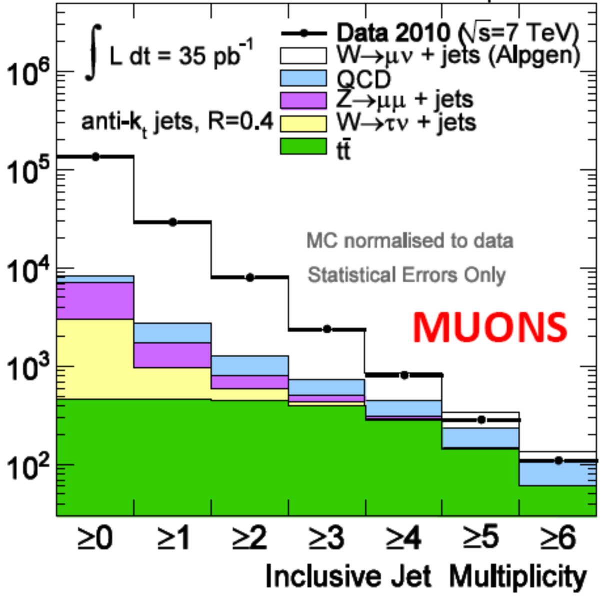




Leptons, missing E_T and jets: W + jets

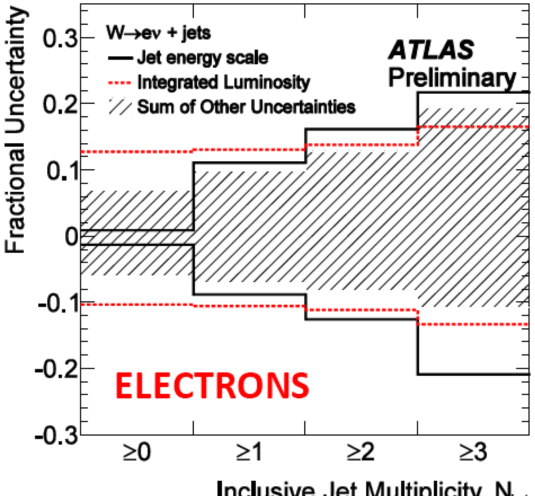
- One of building blocks for SM (top, Higgs) and BSM (SUSY) physics
- Kinematic reach will be far beyond Tevatron
- Measurement uses
  - antikT jets with R=0.4, $p_T^{jet}>20$ GeV, $|\eta_{jet}|<2.8$ and $\Delta R(l,jet)>0.5$
  - electrons and muons have $p_T>20$ GeV
  - leptons (QED radiation in cone of R=0.1 added to 4-vector of lepton, Les Houches: arXiv:1003.1643)
  - $|\eta_{muon}|<2.4$; $|\eta_{electron}|<1.37$ or $1.52<|\eta_{electron}|<2.47$
  - MT(l,mis-ET)>40 GeV and mis-ET>25 GeV
  - cross sections given for fiducial region

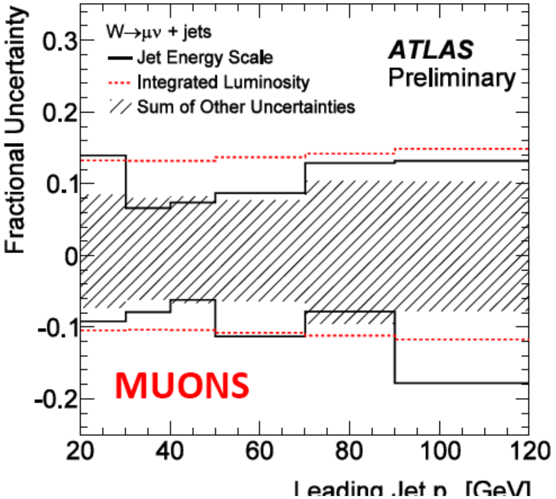


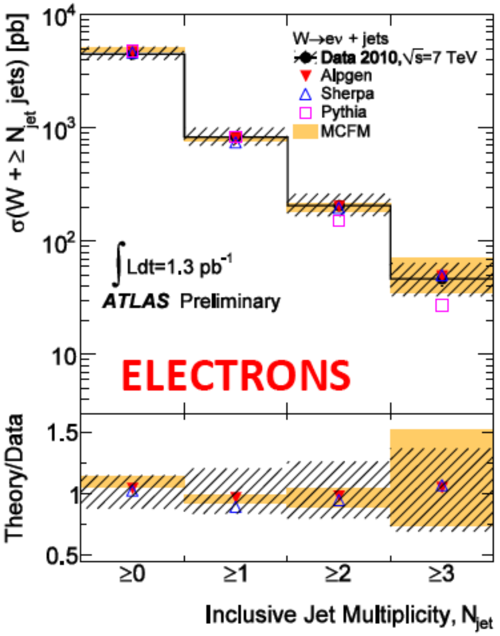


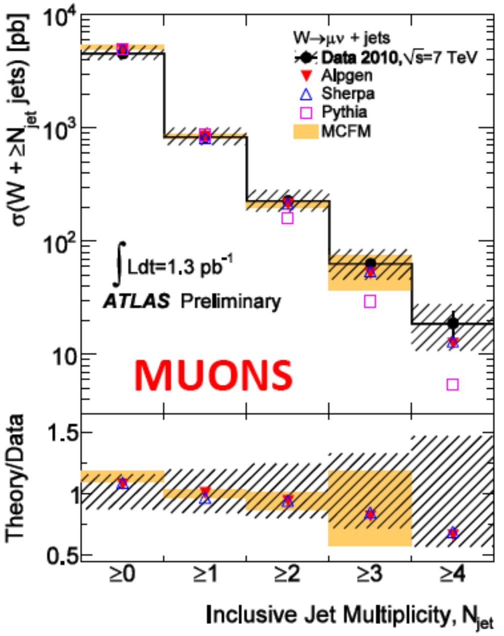
Results

- Uncertainties on JES and luminosity are dominant
    - both should improve in the near future
- Data is in good agreement with NLO predictions from MCFM (for 0-2 jets), with parton level jets corrrected for non-perturbative effects
- Comparisons with W + 3/4 jets (Blackhat + Sherpa) in preparation
- In data on disk now, will have on order of 1000 W + 4 jet events for example









Jet algorithms at NLO

- At LO, a jet is 1 parton
- At NLO, there can be two partons in a jet, life becomes more interesting and we have to start talking about jet algorithms to define jets
  - the addition of the real and virtual terms at NLO cancels the divergences in each

$$d_{ij} = \min\left(p_{T,i}^{2p}, p_{T,j}^{2p}\right)\frac{\Delta R_{ij}^2}{D^2}$$

$$d_{ii} = p_{T,i}^{2p}$$

p=0; C-A
p=1: k_T
p=-1 anti-k_T

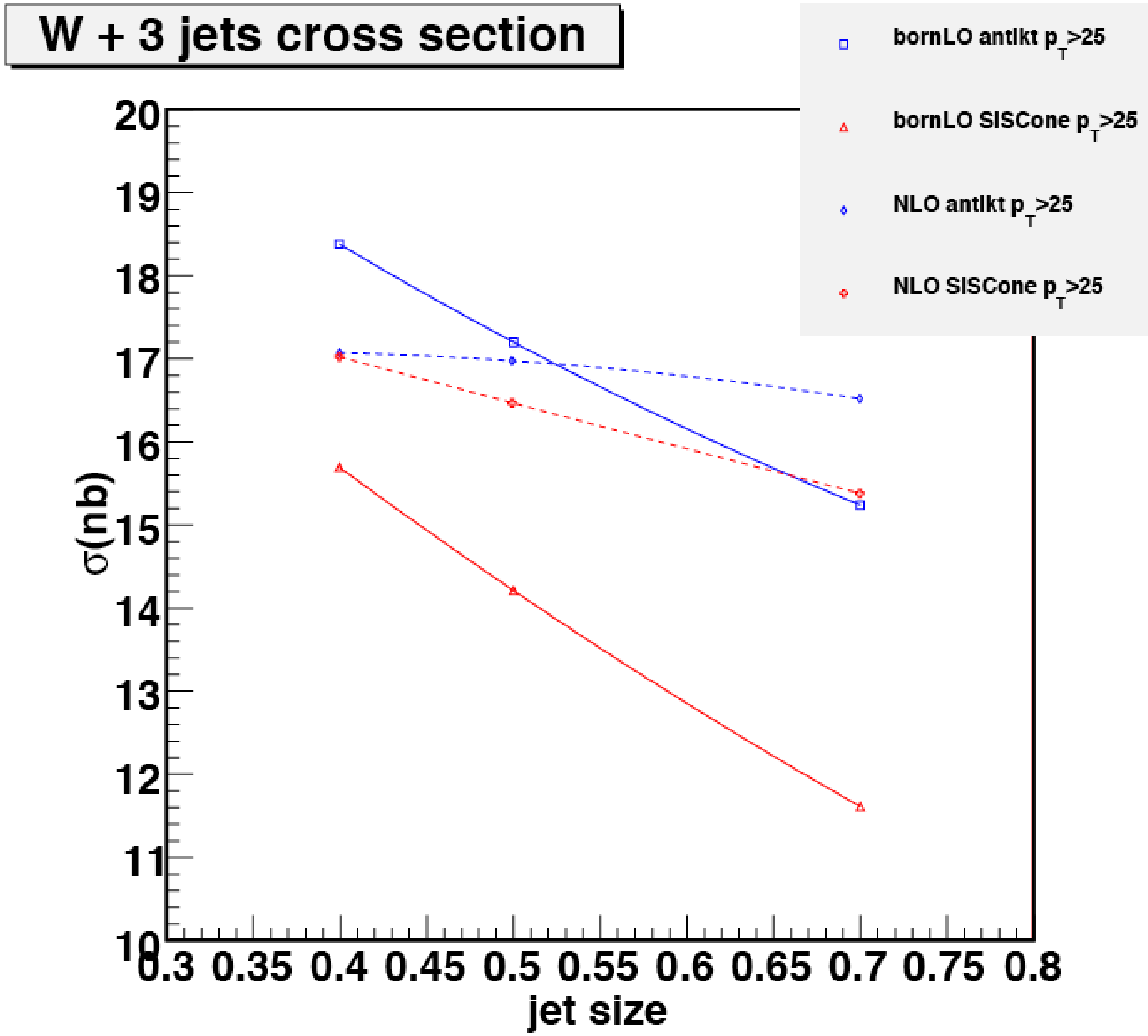
Pierre-Antoine Delsart's *reverse k_T*

- A jet algorithm is based on some measure of localization of the expected collinear spray of particles
- Start with an inclusive list of particles/partons/calorimeter towers/topoclusters
- End with lists of same for each jet
- …and a list of particles… not in any jet; for example, remnants of the initial hadrons
- Two broad classes of jet algorithms
  - cluster according to proximity in space: cone algorithms
  - ATLAS uses SISCone
  - cluster according to proximity in momenta: k_T algorithms
  - ATLAS uses k_T,antik_T

Don’t believe (fixed) LO predictions for jet cross sections

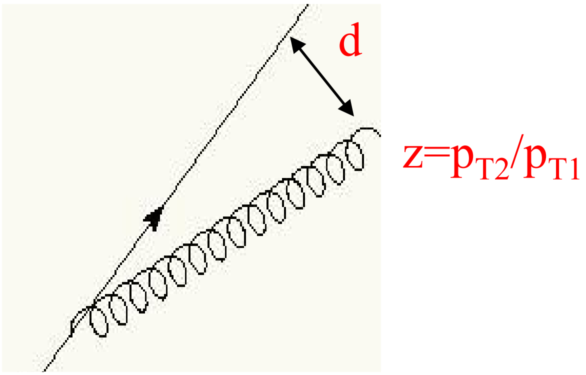
- Often conclusions are made about similarities/differences between jet algorithms based on their behavior for (fixed) LO calculations (where each jet = 1 parton)
- For example, from the LO curves on the right, one would conclude that
  - antikT cross sections are substantially larger than SISCone cross sections
  - cross sections have a large jet size dependence
- This often has little to do with their behavior at NLO (where there can be two partons) or in data/Monte Carlo where there are many partons/hadrons
- The data/MC behavior basically tracks the NLO level, with some differences

…using ROOT ntuples provided by Blackhat+Sherpa



Review: Jet algorithms at LO/NLO

- Remember at LO, 1 parton = 1 jet
- By choosing a jet algorithm with size parameter D, we are requiring any two partons to be > D apart
- The matrix elements have 1/ΔR poles, so larger D means smaller cross sections
    - it's because of the poles that we have to make a ΔR cut
- At NLO, there can be two (or more) partons in a jet and jets for the first time can have some structure
    - we don't need a ΔR cut, since the virtual corrections cancel the collinear singularity from the gluon emission
    - **but there are residual logs that can become important if D is too small**
- Also, increasing the size parameter D increases the phase space for including an extra gluon in the jet, and thus increases the cross section at NLO (in most cases)



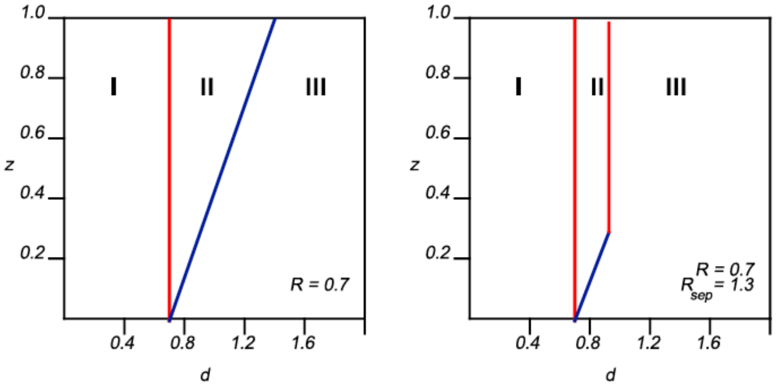


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

For D=R_{cone}, Region I = k_T jets, Region II (nominally) = cone jets; I say nominally because in data not all of Region II is included for cone jets

Jets at NLO: more complications

- Construct what is called a Snowmass potential

shown in Figure 50, where the towers unclustered into any jet are shaded black. A simple way of understanding these dark towers begins by defining a "Snowmass potential" in terms of the 2-dimensional vector $\vec{r} = (y, \phi)$ via

$$V(\vec{r}) = -\frac{1}{2}\sum_j p_{T,j}\left(R_{cone}^2 - (\vec{r_j} - \vec{r})^2\right)\Theta\left(R_{cone}^2 - (\vec{r_j} - \vec{r})^2\right) . \qquad (39)$$

The flow is then driven by the "force" $\vec{F}(\vec{r}) = -\vec{\nabla} V(\vec{r})$ which is thus given by,

$$\begin{aligned}\vec{F}(\vec{r}) &= \sum_j p_{T,j}(\vec{r_j} - \vec{r})\,\Theta\left(R_{cone}^2 - (\vec{r_j} - \vec{r})^2\right)\\ &= \left(\vec{r}_{C(\vec{r})} - \vec{r}\right)\sum_{j\subset C(r)} p_{T,j}, \end{aligned} \qquad (40)$$

related to *pull* in 1001.5027

where $\vec{r}_{C(\vec{r})} = \left(\overline{y}_{C(\vec{r})}, \overline{\phi}_{C(\vec{r})}\right)$ and the sum runs over $j \subset C(\vec{r})$ such that $\sqrt{(y_j - y)^2 + (\phi_j - \phi)^2} \leq R_{cone}$. As desired, this force pushes the cone to the stable cone position.

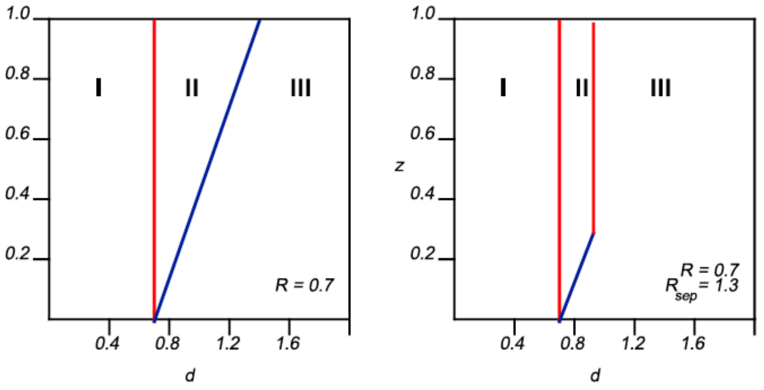


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

- The minima of the potential function indicates the positions of the stable cone solutions
  - the derivative of the potential function is the force that shows the direction of flow of the iterated cone
- The midpoint solution contains both partons

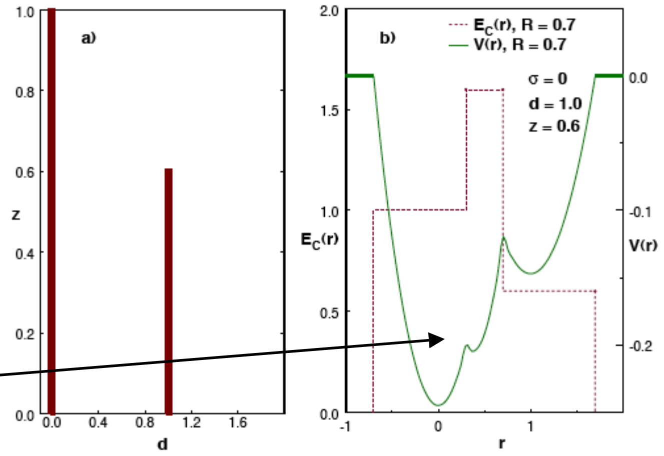
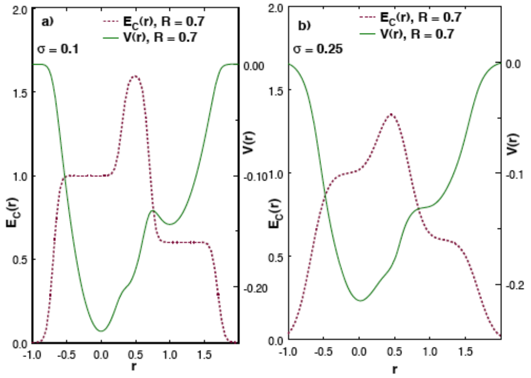


Figure 51. A schematic depiction of a specific parton configuration and the results of applying the midpoint cone jet clustering algorithm. The potential discussed in the text and the resulting energy in the jet are plotted.

Jets in real life

- Jets don't consist of 1 fermi partons but have a spatial distribution
- Can approximate jet shape as a Gaussian smearing of the spatial distribution of the parton energy
  - the effective sigma ranges between around 0.1 and 0.3 depending on the parton type (quark or gluon) and on the parton p_T
- Note that because of the effects of smearing that
  - the midpoint solution is (**almost always**) lost
    - thus region II is effectively truncated to the area shown on the right
  - the solution corresponding to the lower energy parton can also be lost
    - resulting in dark towers



remember the Snowmass potentials

Figure 52. A schematic depiction of the effects of smearing on the midpoint cone jet clustering algorithm.

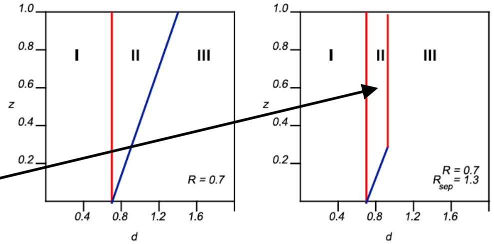


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

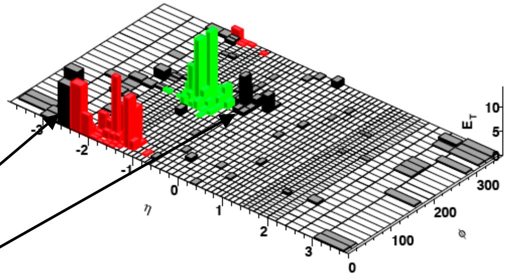


Figure 50. An example of a Monte Carlo inclusive jet event where the midpoint algorithm has left substantial energy unclustered.

Jets in real life

- In NLO theory, can mimic the impact of the truncation of Region II by including a parameter called R_{sep}
  - only merge two partons if they are within R_{sep}*R_{cone} of each other
    - R_{sep}~1.3
  - ~4-5% effect on the theory cross section; effect is smaller with the use of p_T rather than E_T
  - really upsets the theorists (but there are also disadvantages)
- Dark tower effect is also on order of few (<5)% effect on the (experimental) cross section
- Dark towers affect every cone algorithm

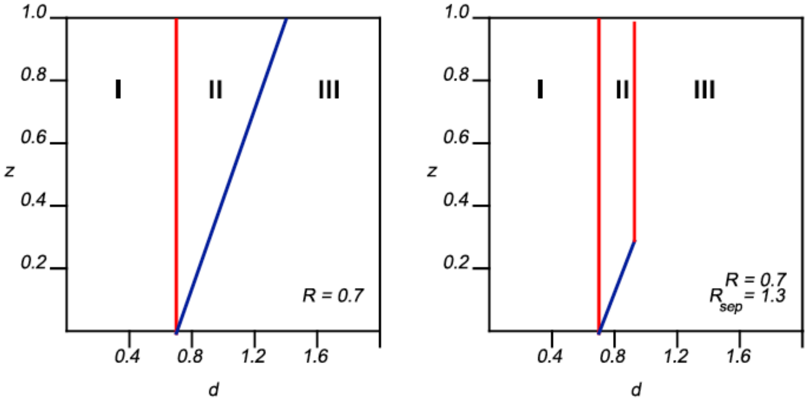
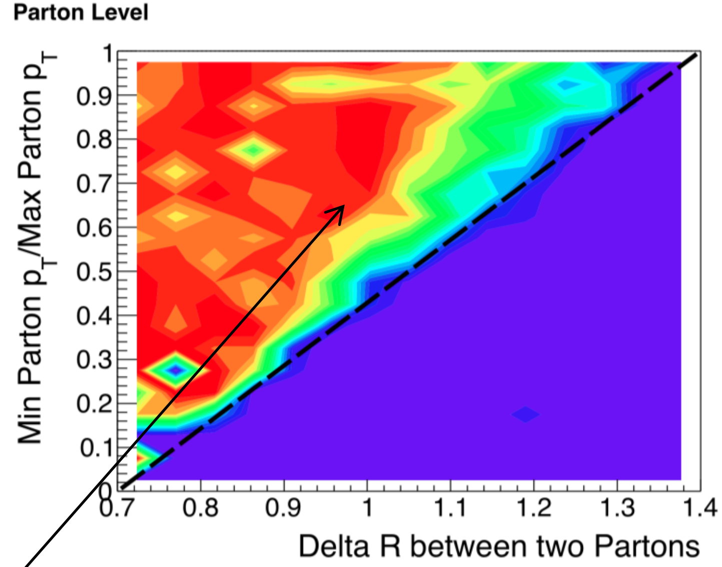
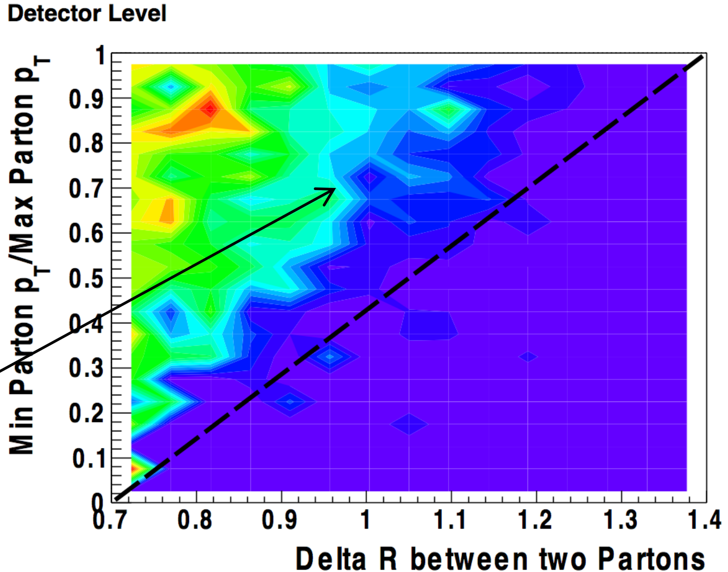


Figure 22. The parameter space (d,Z) for which two partons will be merged into a single jet.

One of those LO/NLO differences

- Take W + 2 parton events (ALPGEN+PYTHIA), run SISCone 0.7 algorithm on parton level, hadron level (not shown) and topocluster level
- Plot the probability for the two sub-jets to merge as a function of the separation of the original two partons in ΔR
- Color code:
  - red: high probability for merging
  - blue: low probability for merging
  - everything for ΔR<0.7 is merged for SISCone (and antikT)
- Parton level reconstruction agrees with naïve expectation
  - everything above the diagonal should be reconstructed as one jet
- Topocluster level reconstruction shows that widely separated sub-jets will not be reconstructed into the


Parton Level


Detector Level

Scale choices

scales related to H_T work at both LO and NLO; CKKW also seems to agree well with NLO predictions in shape

Les Houches NLM proceedings

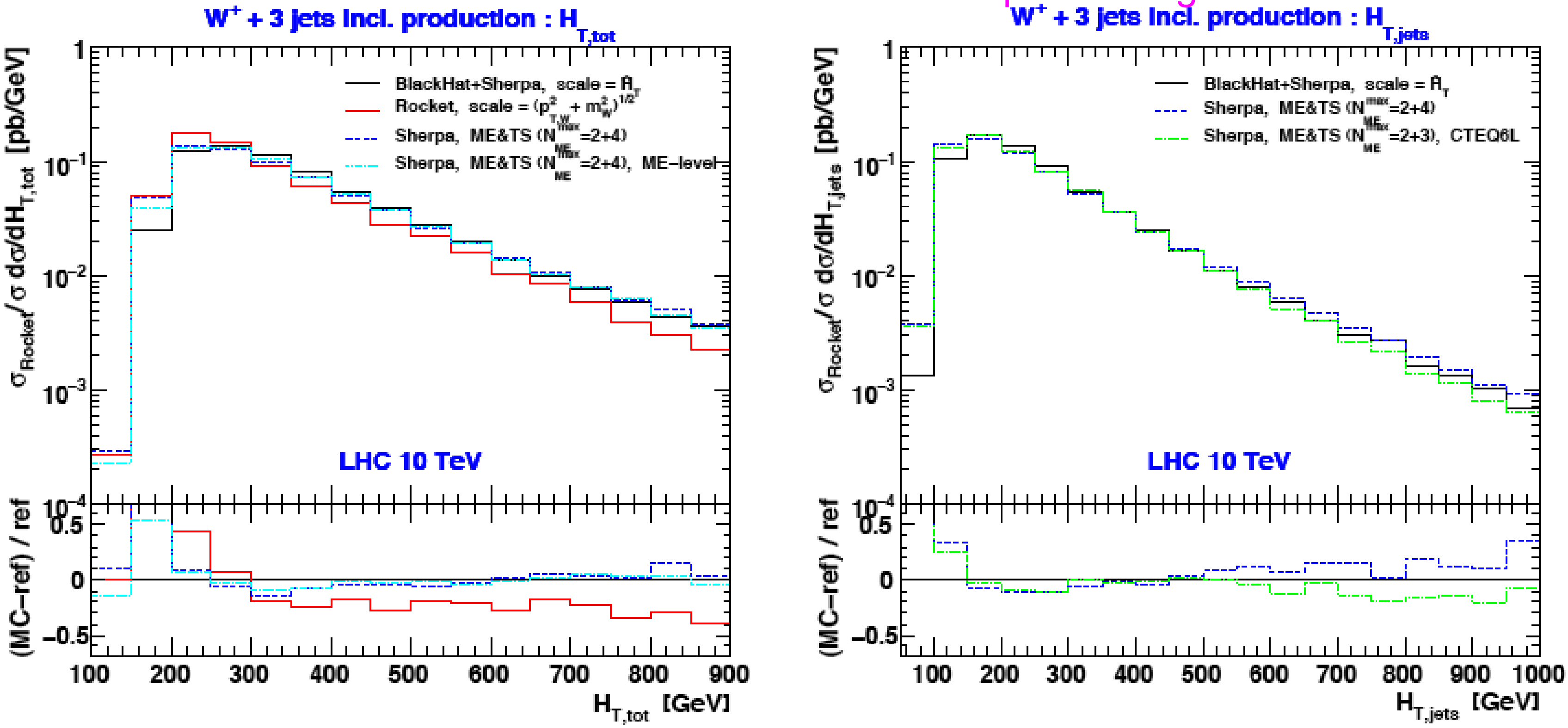


Fig. 19: H_T and $H_{T,\text{jets}}$ distributions in inclusive $W^+ + 3$ jet production at the LHC. NLO predictions obtained from BLACKHAT+SHERPA (black line) and ROCKET (red line) are compared to LO results from SHERPA using the ME&TS merging. All curves have been rescaled to the ROCKET NLO cross section of Table 5; the BLACKHAT+SHERPA prediction is used as the reference; cuts and parameters are detailed in Section 12.2

Scale dependence: jet algorithms

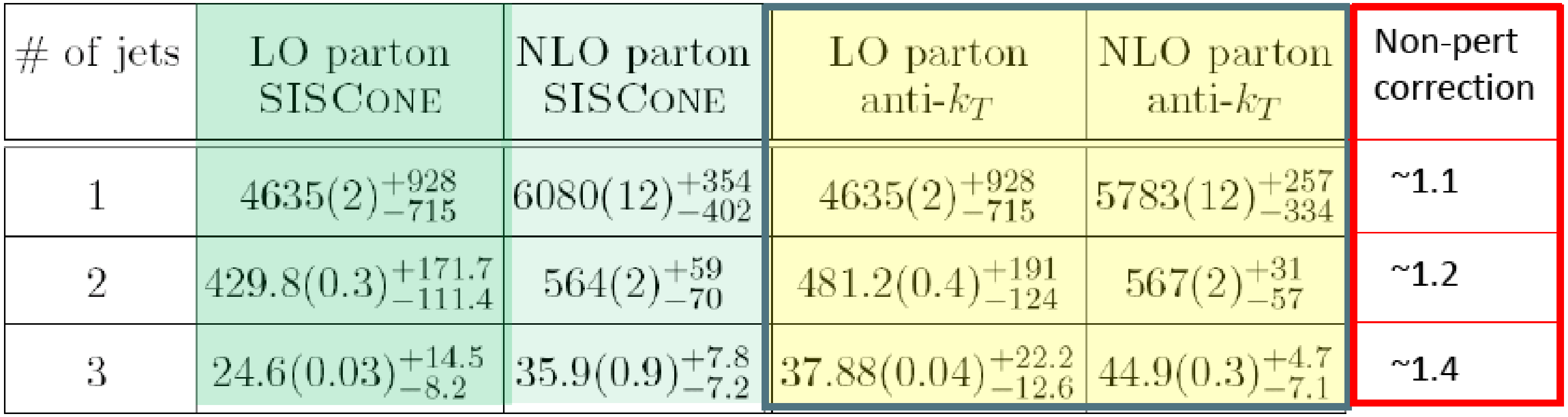
- Look at results for SISCone/antikT; antikT cross sections larger than SISCone, smaller scale dependence?

Multi-jet systematics: jet-algorithms Z+n jets.

CDF: Phys. Rev. Lett. 100, 102001 (2008)
[BlackHat: 0912.4927, 1004.1659]
See also talk by J. Huston

σ in [fb]

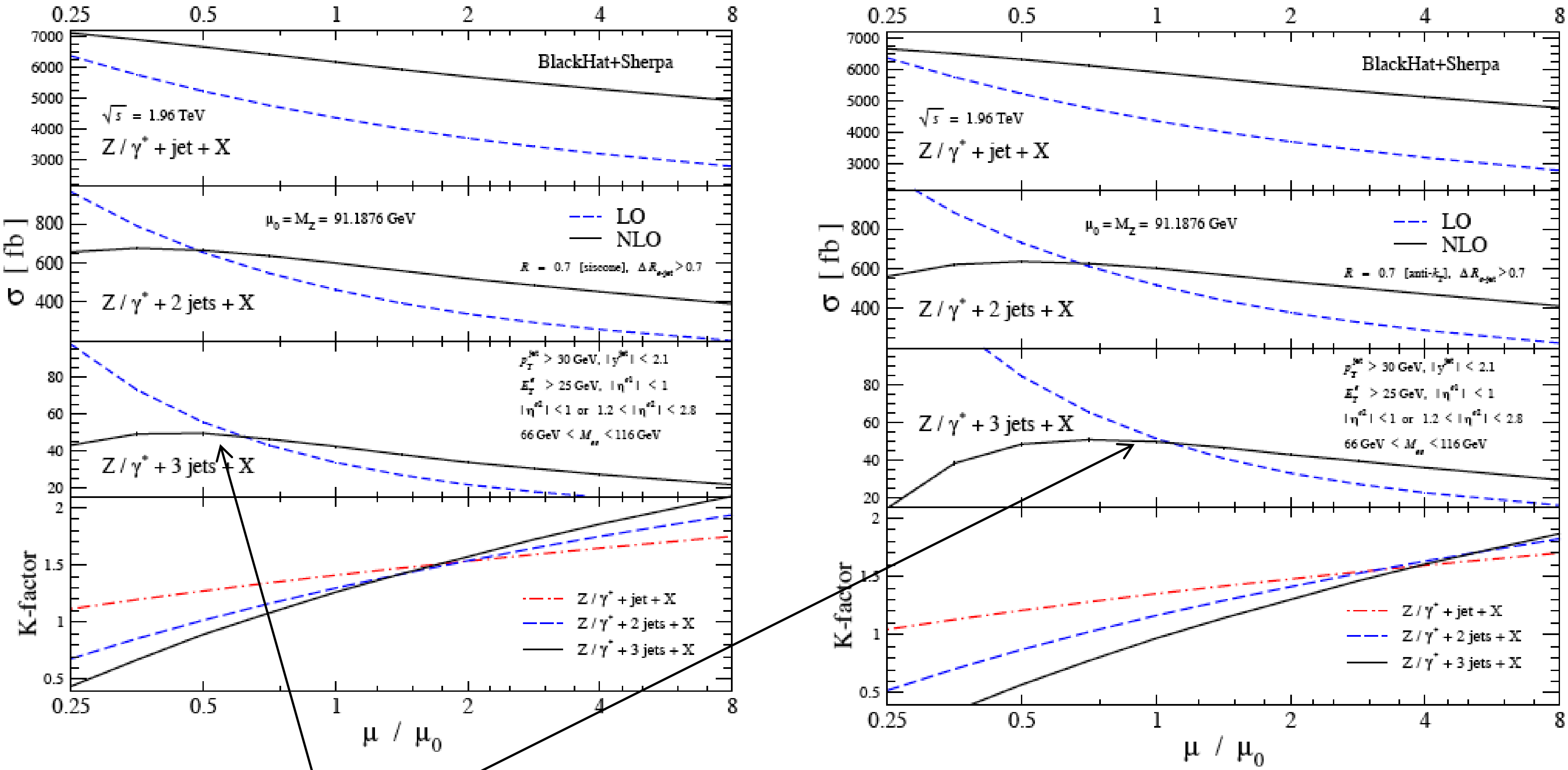
Tevatron



# of jets	LO parton SISCone	NLO parton SISCone	LO parton anti-k_T	NLO parton anti-k_T	Non-pert correction
1	$4635(2)^{+928}_{-715}$	$6080(12)^{+354}_{-402}$	$4635(2)^{+928}_{-715}$	$5783(12)^{+257}_{-334}$	~1.1
2	$429.8(0.3)^{+171.7}_{-111.4}$	$564(2)^{+59}_{-70}$	$481.2(0.4)^{+191}_{-124}$	$567(2)^{+31}_{-57}$	~1.2
3	$24.6(0.03)^{+14.5}_{-8.2}$	$35.9(0.9)^{+7.8}_{-7.2}$	$37.88(0.04)^{+22.2}_{-12.6}$	$44.9(0.3)^{+4.7}_{-7.1}$	~1.4

H. Ita, SLAC Hadronic Final State Forum

Z + 3 jets: scale dependence

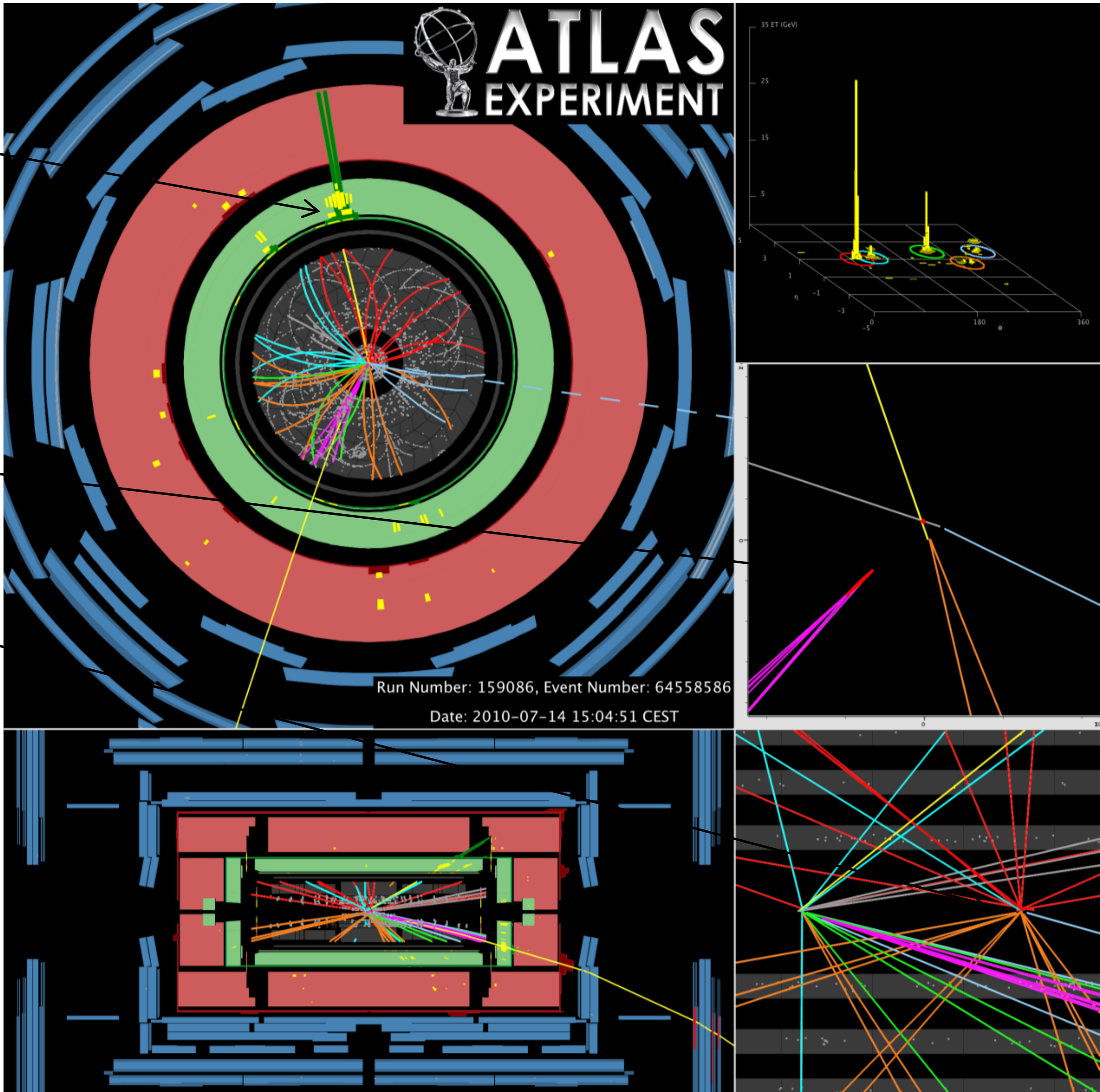


Note that peak cross sections are actually quite close; the cross sections just peak at different scales.

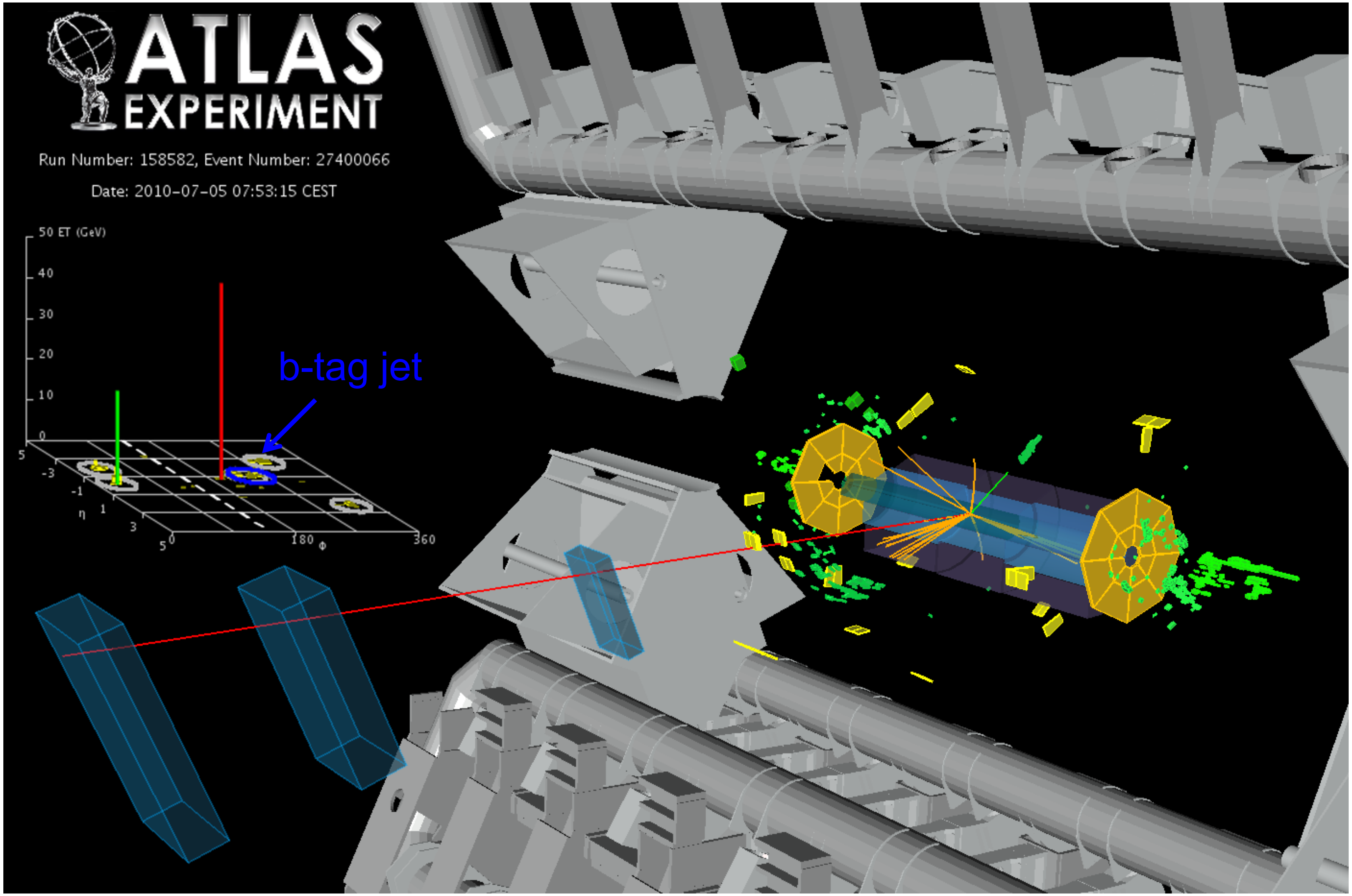
1004.1659

Rediscovering top

- Electron + jets event
- Secondary vertex tagged jet
- Extra pileup interaction

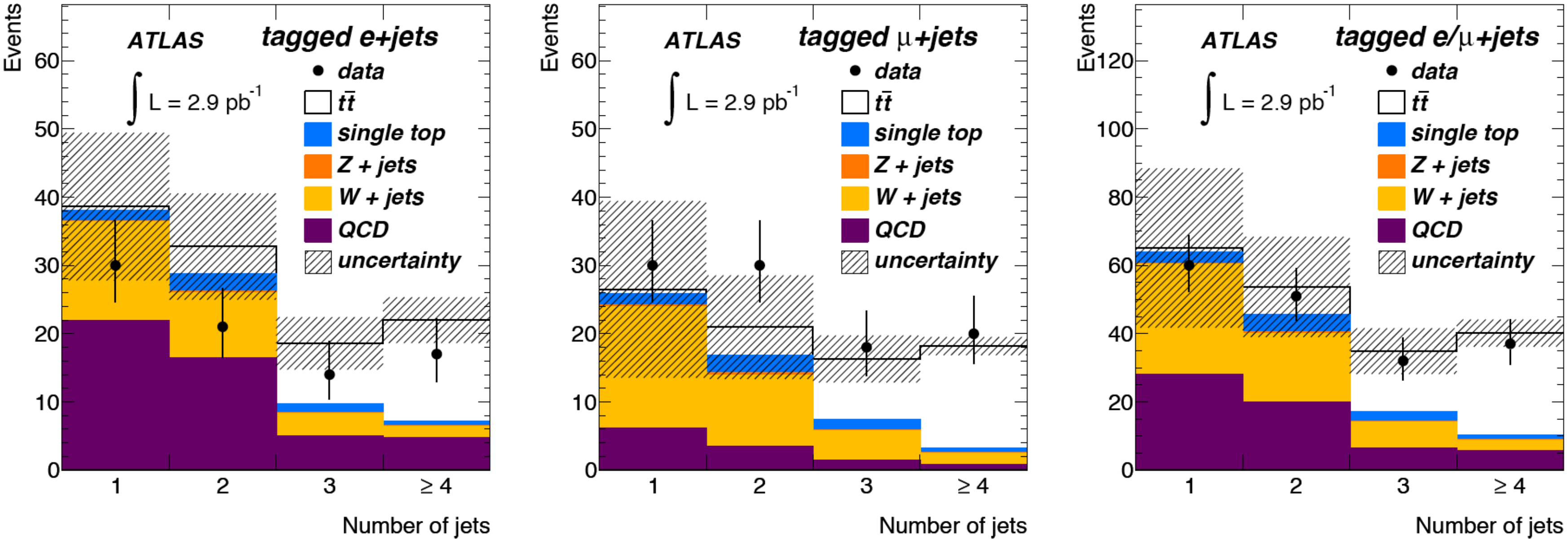


e-μ event



b-tag jet

Top Rediscovery

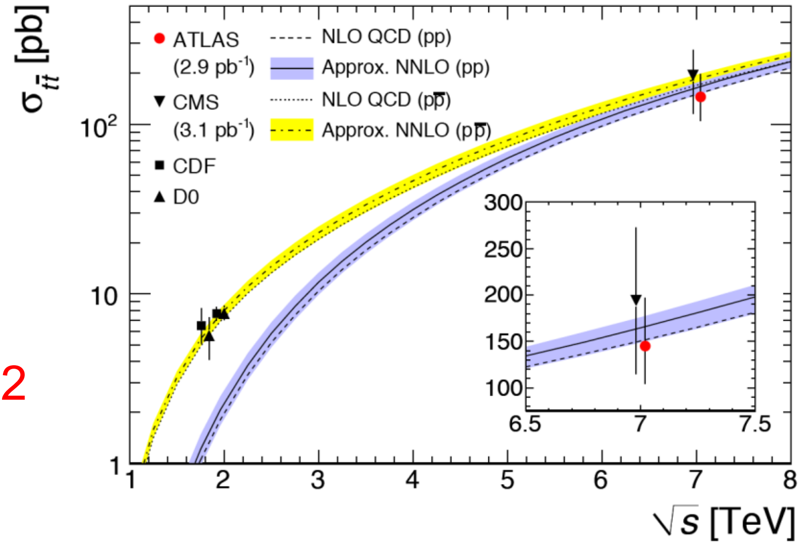


- In 2.9 pb^{-1} of data, 37 lepton + jets top pair candidates and 9 dilepton top pair candidates
- Combination of lepton + jets and dilepton results

$$\sigma = 145 \pm 31^{+42}_{-27}\ pb$$

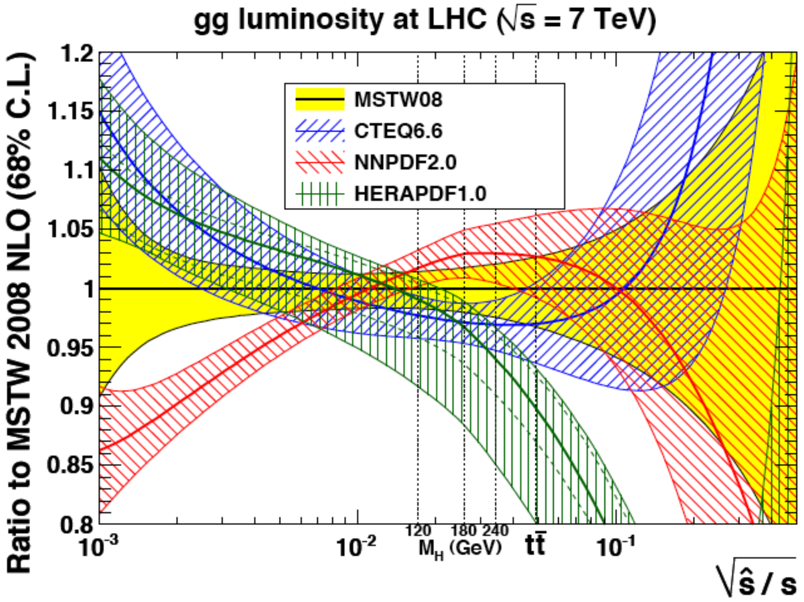
arXiv:1012.1792v2

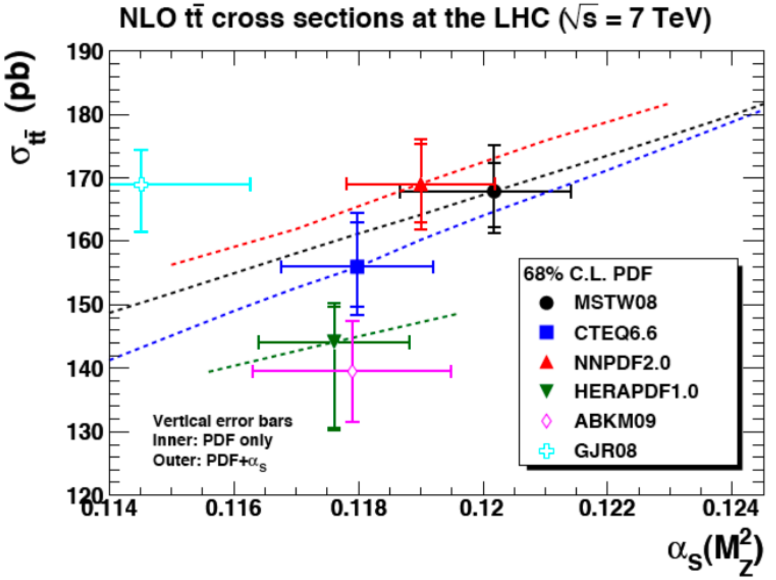
4.8 σ significance



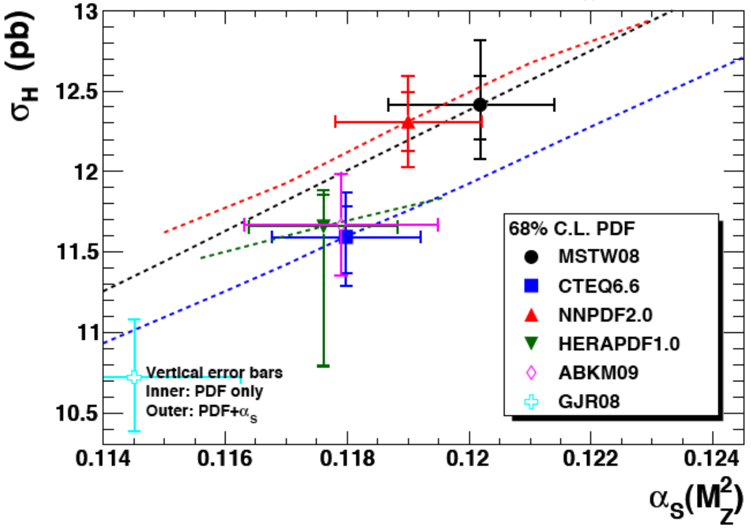
Aside: Some more results from the benchmarking

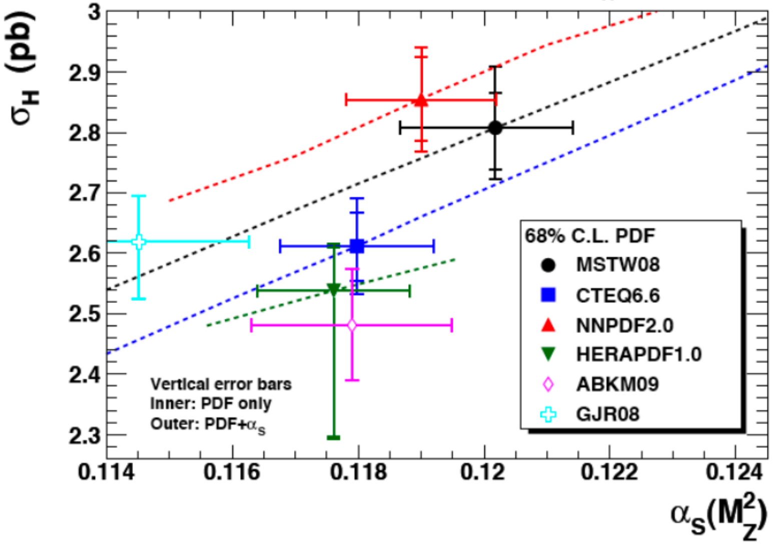
- …from G. Watt’s presentation at PDF4LHC meeting on March 26
- Similar gluon-gluon luminosity uncertainty bands, as noted before
- Cross sections fall into two groups, outside 68% CL error bands
- But, slide everyone’s prediction along the α_s curve to 0.119 (for example) and predictions agree reasonably well
  - ◆ within 68% CL PDF errors

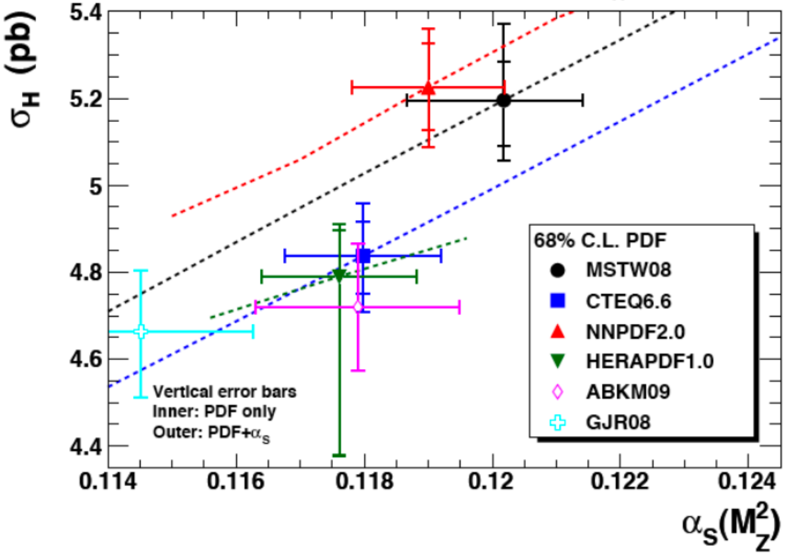




More benchmarking


NLO gg→H at the LHC ($\sqrt{s}$ = 7 TeV) for M_H = 120 GeV


NLO gg→H at the LHC ($\sqrt{s}$ = 7 TeV) for M_H = 240 GeV


NLO gg→H at the LHC ($\sqrt{s}$ = 7 TeV) for M_H = 180 GeV

Correlations with Z, tT

Define a correlation cosine between two quantities

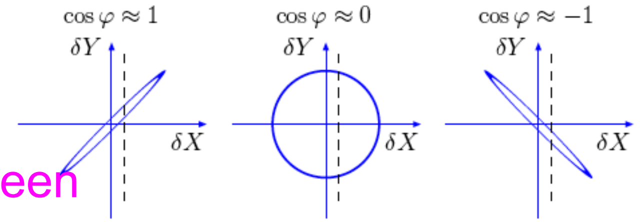


Figure 1: Dependence on the correlation ellipse formed in the $\Delta X - \Delta Y$ plane on the value of the correlation cosine $\cos\varphi$.

- If two cross sections are very correlated, then cosϕ~1
- …uncorrelated, then cosϕ~0
- …anti-correlated, then cosϕ~-1

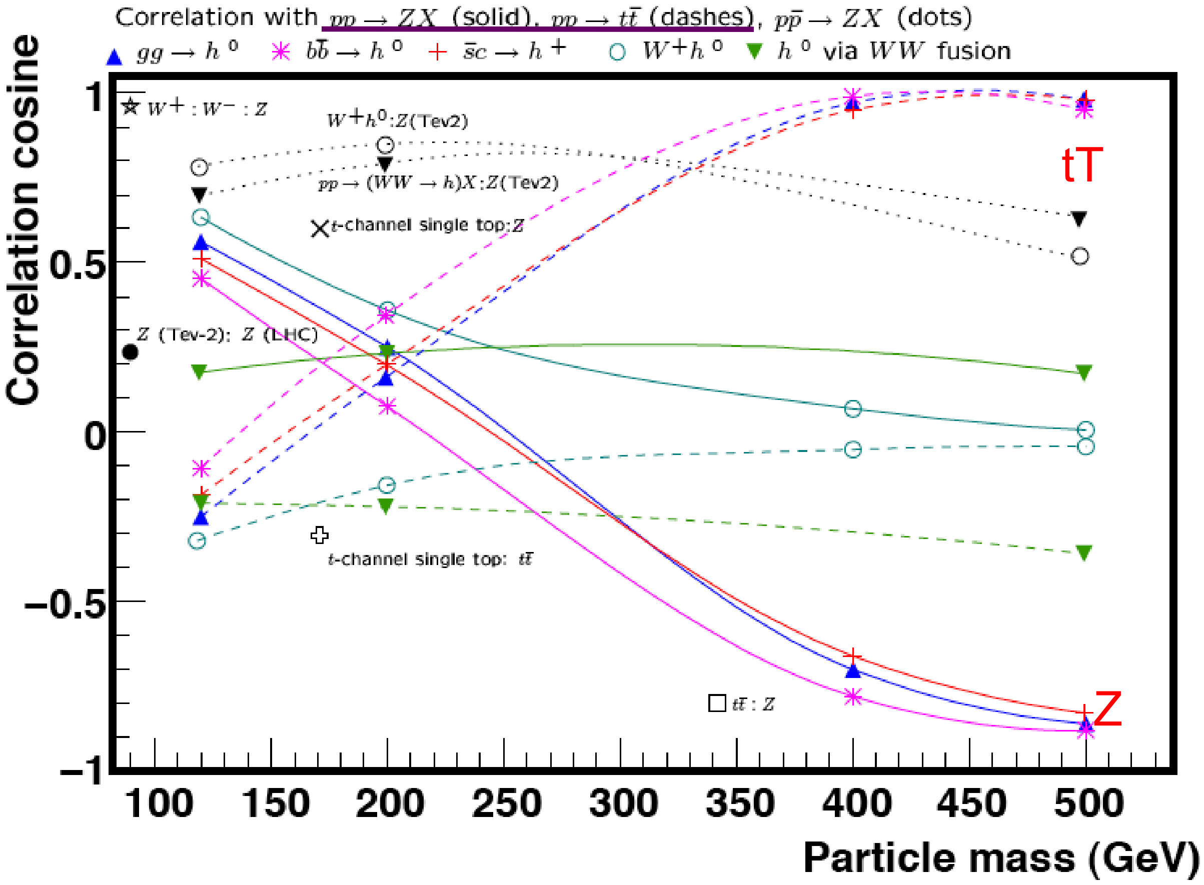
- W and Z will be heavily used for cross section normalization

- Note that correlation curves to Z and to tT are mirror images of each other

- By knowing the pdf correlations, can reduce the uncertainty for a given cross section in ratio to a benchmark cross section **iff** cos ϕ > 0;e.g. $\Delta(\sigma_W+/\sigma_Z)$~1%

- If cos ϕ < 0, pdf uncertainty for one cross section normalized to a benchmark cross section is larger

- So, for gg->H(500 GeV); pdf uncertainty is 4%; $\Delta(\sigma_H/\sigma_Z)$~8%

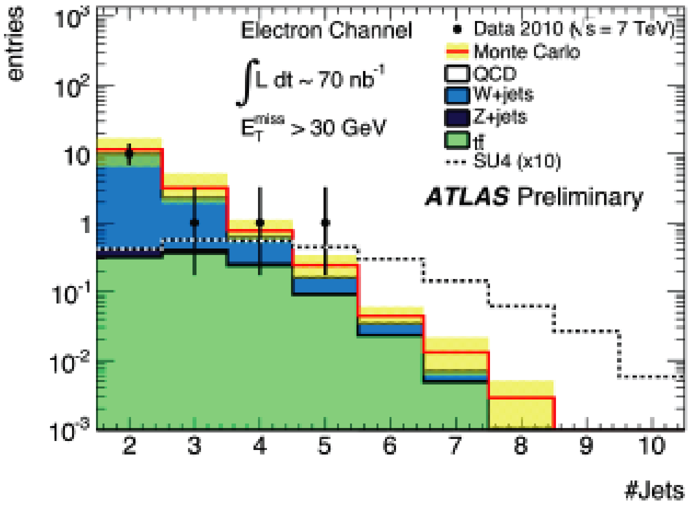


Back to ATLAS: new physics searches

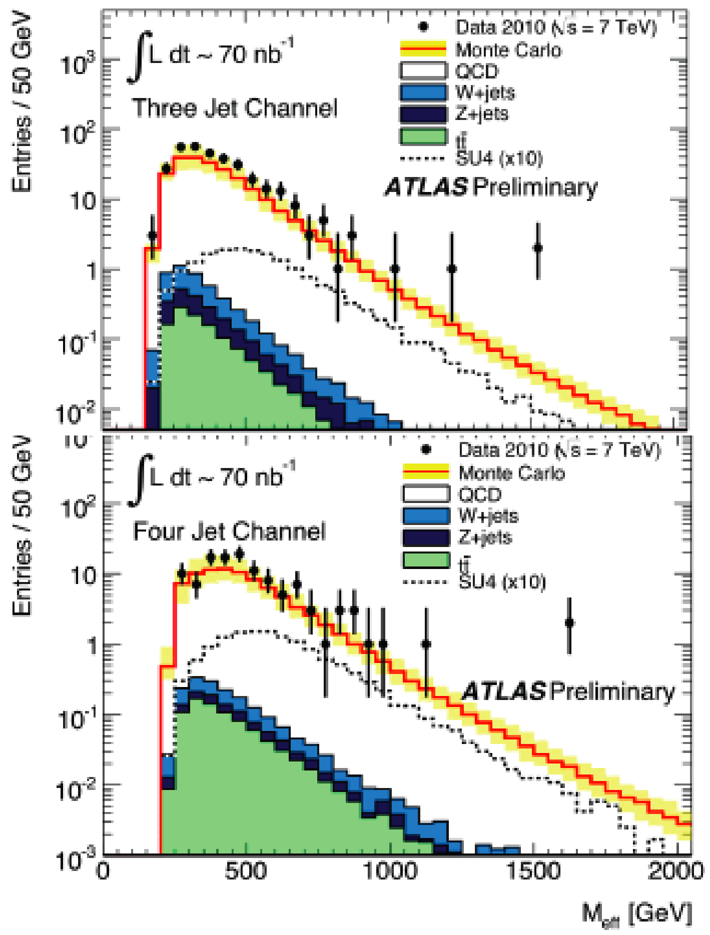
General search strategy for heavy squark/gluino production and decay to invisible Lightest Supersymmetric Particles (LSPs)

Require jets and significant missing E_T; measure “effective mass” as estimate of supersymmetry mass scale

$$M_{\rm eff} \equiv \sum_{i=1}^{n} \left|\mathbf{p}_{\rm T}^{(i)}\right| + E_{\rm T}^{\rm miss}$$



“0-lepton searches” after missing E_T cut



Didn’t find any: so far

…but

Exciting candidate…

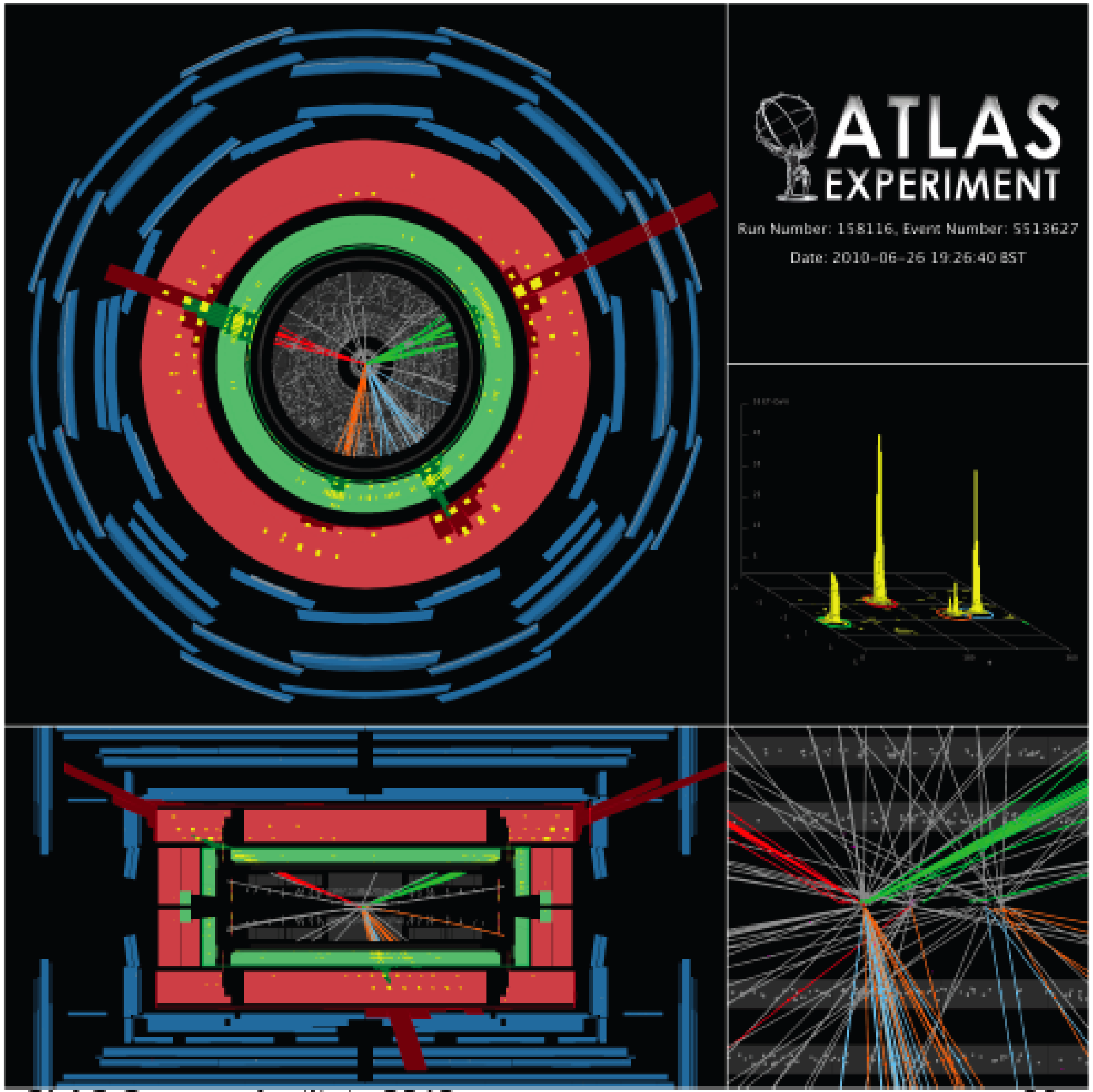
Jet + missing ET selection
4 high-energy jets
(same primary vertex)

Effective mass of 1.65 TeV
(incl. 4 jets)

…with a few problems

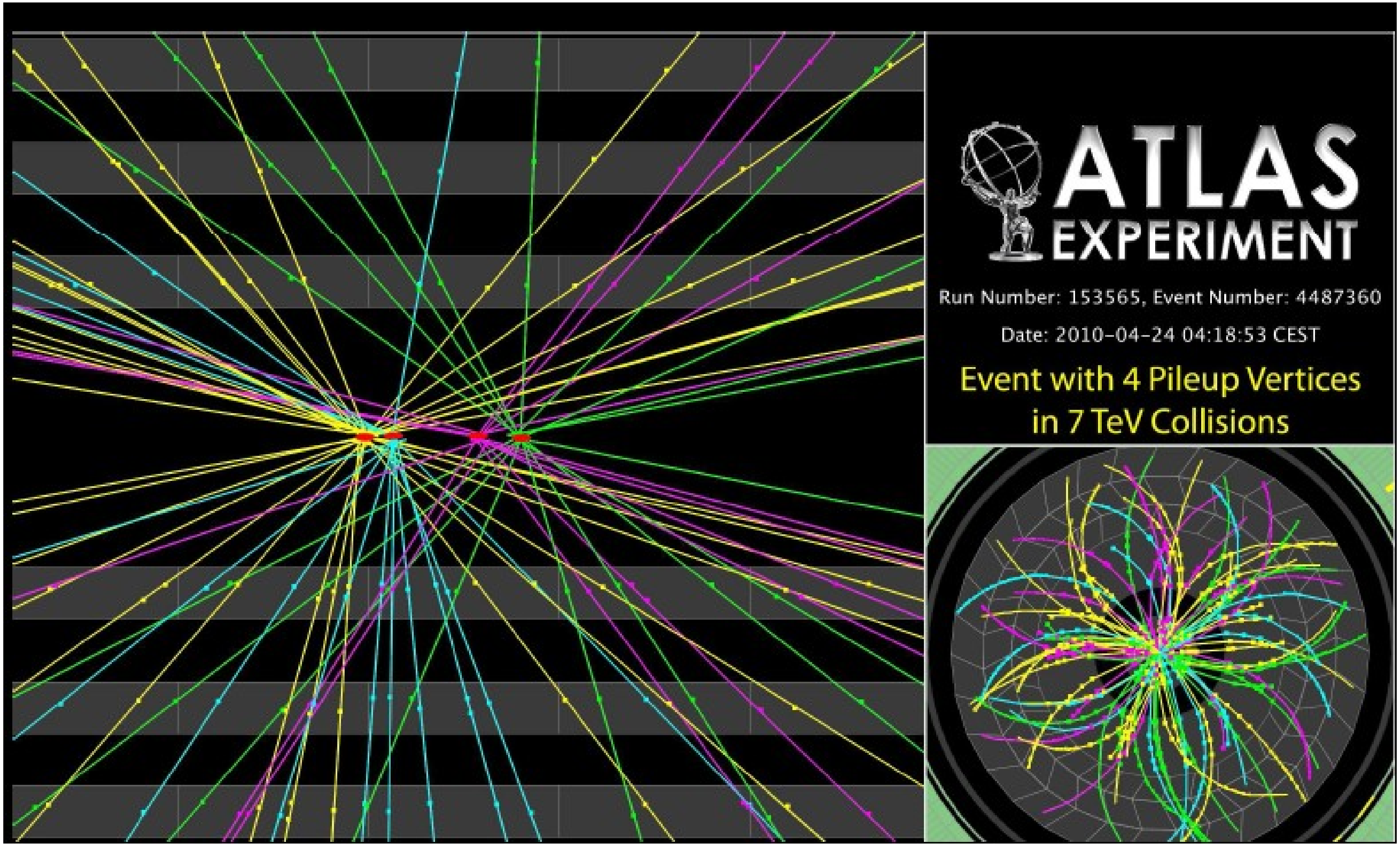
Missing ET ≈ 100 GeV, but lies in direction of vertex-tagged jet (semilep decay?)

Event does not pass selection criteria for Δϕ(jet, ptmiss) nor ratio of missing ET to effective mass



Higher luminosity (and energy) is coming

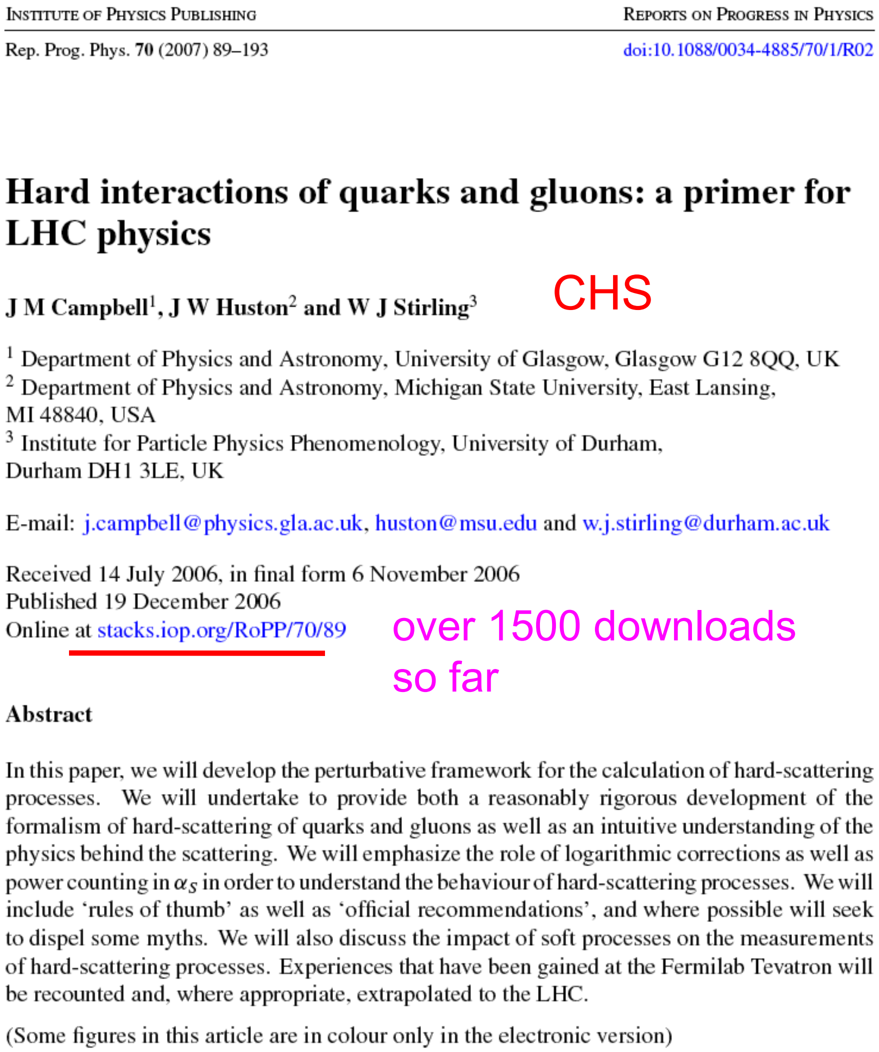
…and with it precision comparisons of data to theory



Summary

- We have an opportunity (forced on us) to understand the QCD environment at the LHC before we reach discover-potential integrated luminosities
- We have the ability (with the ATLAS detector) to make more detailed measurements of final states including jets than any previous collider detector
- ATLAS/LHC are working well, taking and analyzing data, putting together the SM benchmarks needed for robust physics at 7 TeV
- …thanks to ATLAS colleagues whose transparencies I've borrowed

Some references



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Hard interactions of quarks and gluons: a primer for LHC physics

CHS

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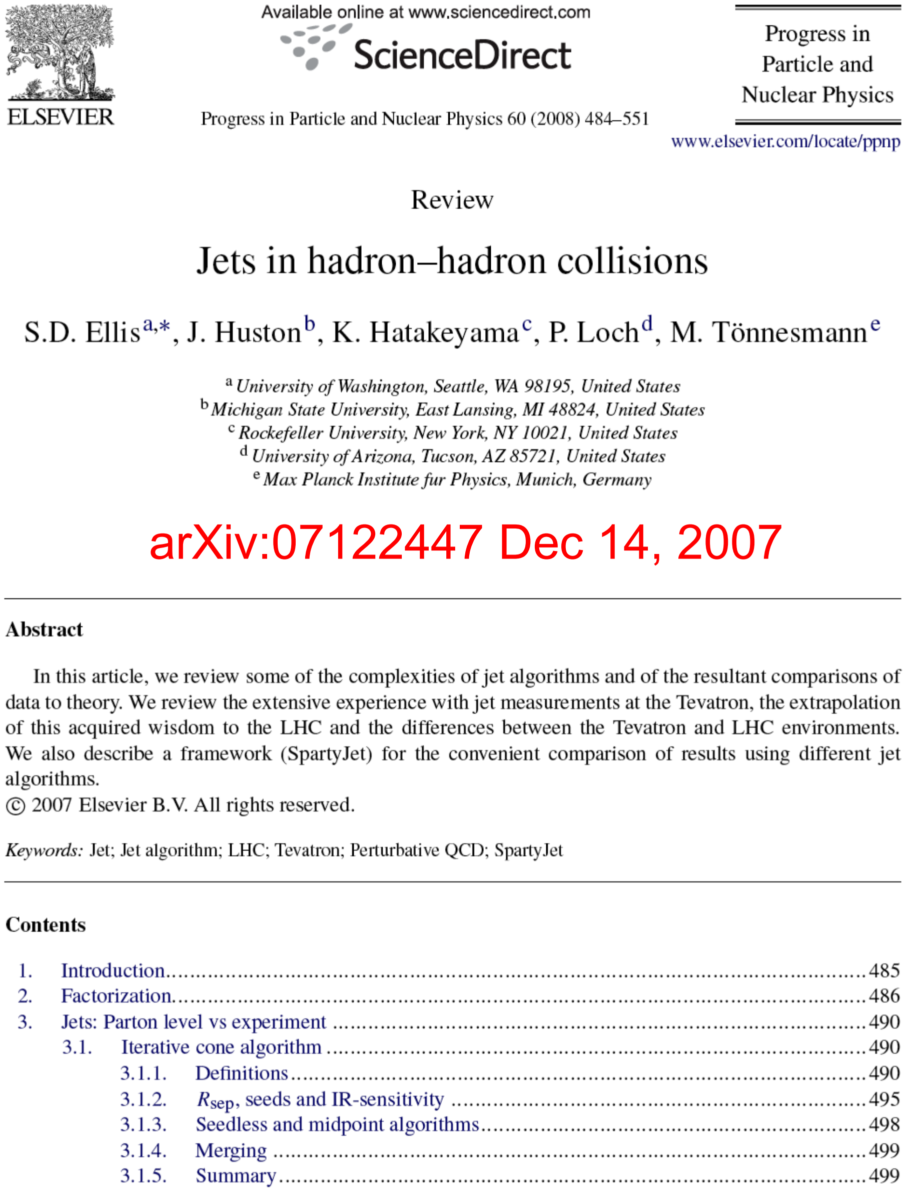
Abstract

In this paper, we will develop the perturbative framework for the calculation of hard-scattering processes. We will undertake to provide both a reasonably rigorous development of the formalism of hard-scattering of quarks and gluons as well as an intuitive understanding of the physics behind the scattering. We will emphasize the role of logarithmic corrections as well as power counting in α_S in order to understand the behaviour of hard-scattering processes. We will include 'rules of thumb' as well as 'official recommendations', and where possible will seek to dispel some myths. We will also discuss the impact of soft processes on the measurements of hard-scattering processes. Experiences that have been gained at the Fermilab Tevatron will be recounted and, where appropriate, extrapolated to the LHC.

(Some figures in this article are in colour only in the electronic version)

goal is to provide a reasonably global picture of LHC calculations



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Progress in Particle and Nuclear Physics

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Review

Jets in hadron–hadron collisions

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arXiv:07122447 Dec 14, 2007

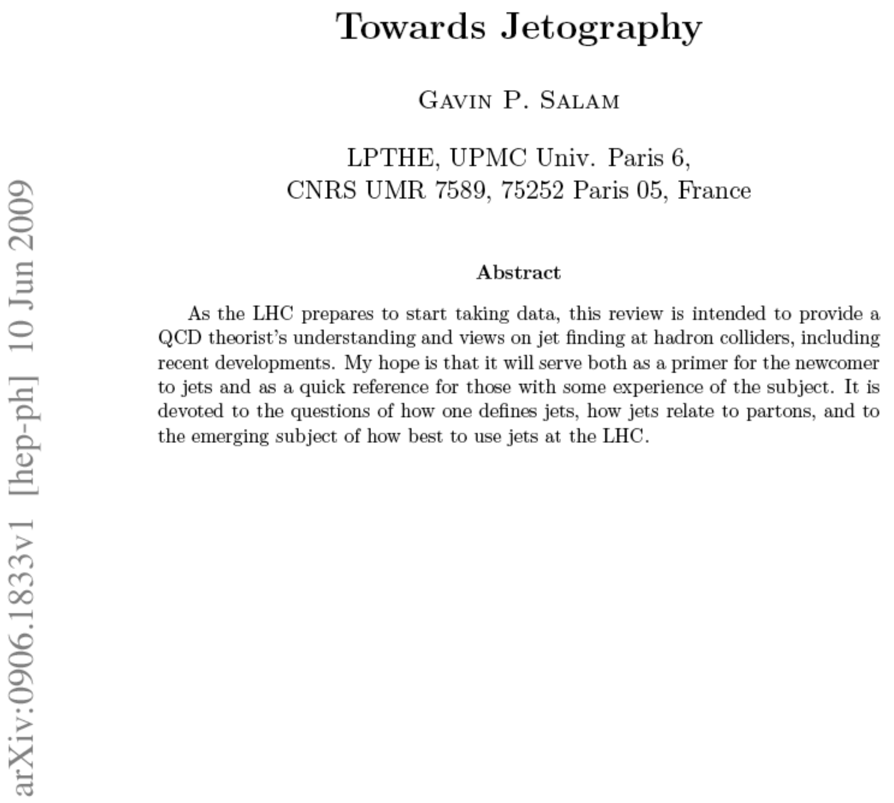
Abstract

In this article, we review some of the complexities of jet algorithms and of the resultant comparisons of data to theory. We review the extensive experience with jet measurements at the Tevatron, the extrapolation of this acquired wisdom to the LHC and the differences between the Tevatron and LHC environments. We also describe a framework (SpartyJet) for the convenient comparison of results using different jet algorithms.

Keywords: Jet; Jet algorithm; LHC; Tevatron; Perturbative QCD; SpartyJet

Contents

More references



arXiv:0906.1833v1 [hep-ph] 10 Jun 2009

Towards Jetography

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Abstract

As the LHC prepares to start taking data, this review is intended to provide a QCD theorist's understanding and views on jet finding at hadron colliders, including recent developments. My hope is that it will serve both as a primer for the newcomer to jets and as a quick reference for those with some experience of the subject. It is devoted to the questions of how one defines jets, how jets relate to partons, and to the emerging subject of how best to use jets at the LHC.

arXiv:1003.1241v1 [hep-ph] 5 Mar 2010

THE SM AND NLO MULTILEG WORKING GROUP:
Summary Report

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SpartyJet

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Sparty

http://projects.hepforge.org/spartyjet/

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K-factors

- Often we work at LO by necessity (parton shower Monte Carlos), but would like to know the impact of NLO corrections
- K-factors (NLO/LO) can be a useful short-hand for this information
- But caveat emptor; the value of the K-factor depends on a number of things
  - PDFs used at LO and NLO
  - scale(s) at which the cross sections are evaluated
- And often the NLO corrections result in a shape change, so that one K-factor is not sufficient to modify the LO cross sections

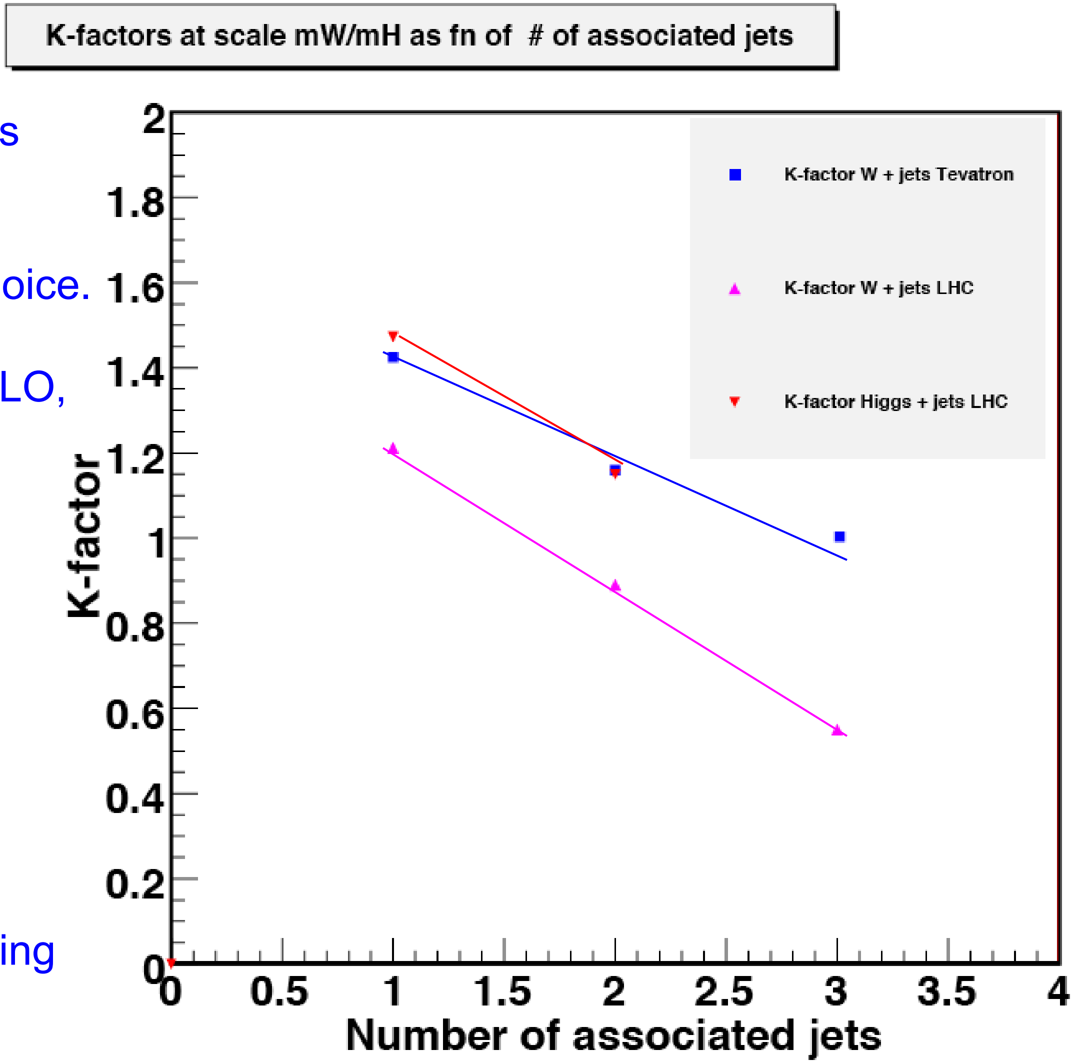
Is the K-factor (at m_W) at the LHC surprising?

The K-factors for W + jets (p_T>30 GeV/c) fall near a straight line, as do the K-factors for the Tevatron. By definition, the K-factors for Higgs + jets fall on a straight line.

Nothing special about m_W; just a typical choice.

The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we understand the behavior with the associated number of jets?

Related to this is:
- understanding the reduced scale dependences/pdf uncertainties for cross section ratios we have been discussing
-scale choices at LO for cross sections uncalculated at NLO



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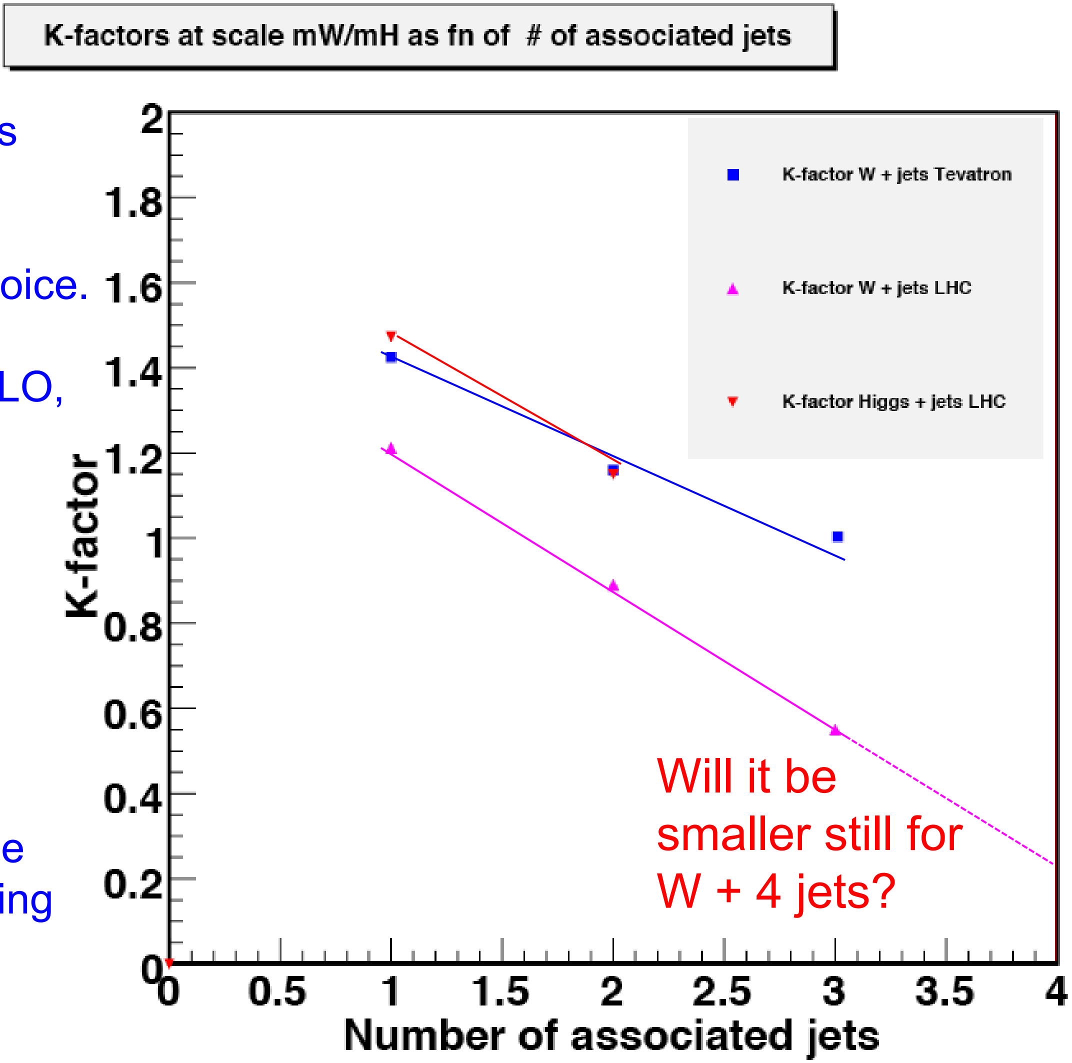
Nothing special about m_W; just a typical choice.

The only way to know a cross section to NLO, say for W + 4 jets or Higgs + 3 jets, is to calculate it, but in lieu of the calculations, especially for observables that we have deemed important at Les Houches, can we make rules of thumb?

Related to this is:

- understanding the reduced scale dependences/pdf uncertainties for the cross section ratios we have been discussing
- scale choices at LO for cross sections calculated at NLO
- scale choices at LO for cross sections uncalculated at NLO

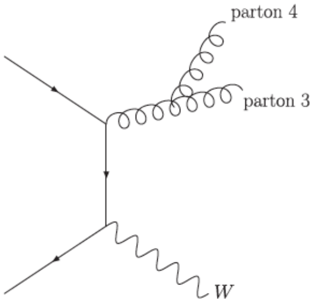


Will it be smaller still for W + 4 jets?

To understand this further, we have to discuss jet algorithms

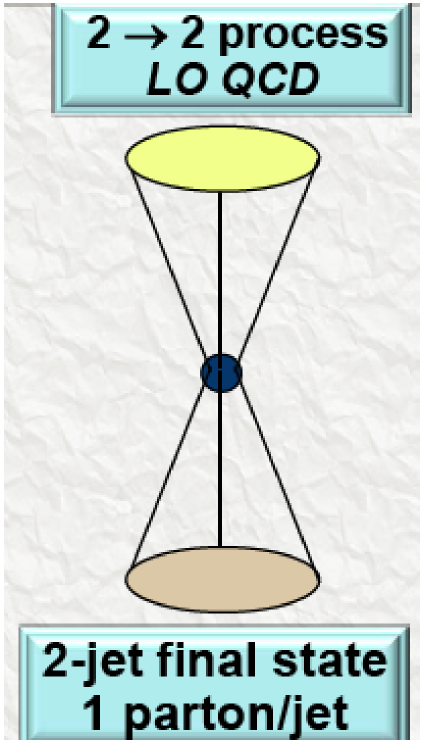
Jet algorithms at LO

- At (fixed) LO, 1 parton = 1 jet
    - why not more than 1? I have to put a ΔR cut on the separation between two partons; otherwise, there's a collinear divergence. LO parton shower programs effectively put in such a cutoff
    - Remember the collinear singularity

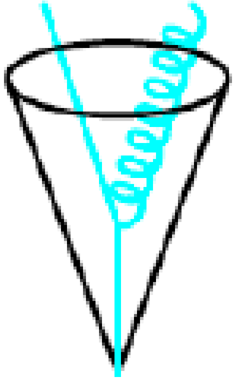


$$\log\left(\frac{1}{\Delta R_{34}}\right)$$

- But at NLO, I have to deal with more than 1 parton in a jet, and so now I have to talk about how to cluster those partons
    - i.e. jet algorithms

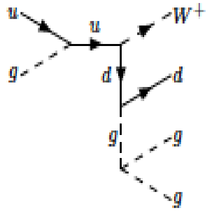

2 → 2 process
LO QCD

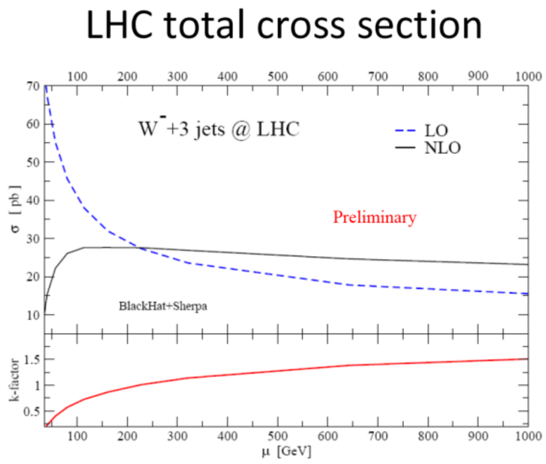
2-jet final state
1 parton/jet

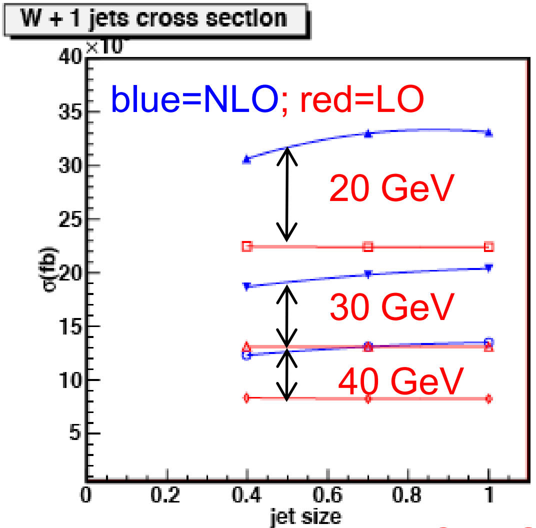


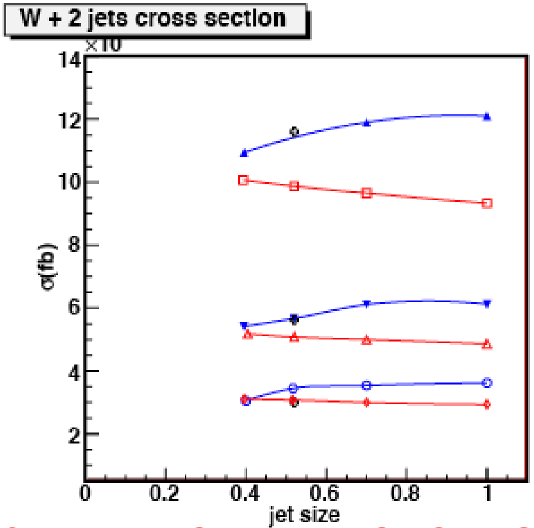
Is the K-factor (at m_W) at the LHC surprising?

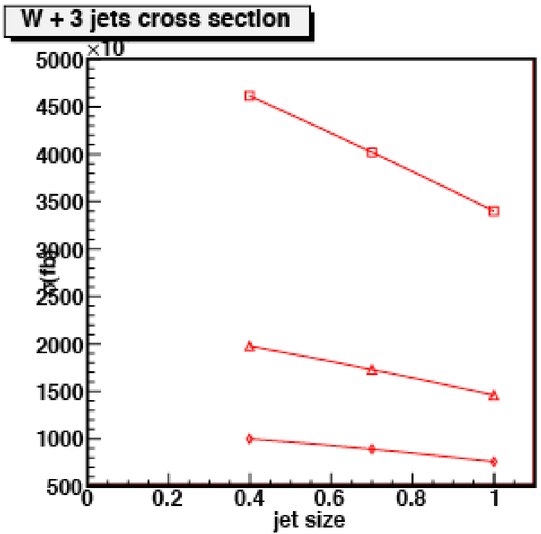
The problem is not the NLO cross section; that is well-behaved.
The problem is that the LO cross section sits 'too-high'. The reason (one of them) for this is that we are 'too-close' to the collinear pole (R=0.4) leading to an enhancement of the LO cross section (double-enhancement if the gluon is soft (~20 GeV/c)). Note that at LO, the cross section increases with decreasing R; at NLO it decreases.
The collinear dependence gets stronger as n_{jet} increases.
The K-factors for W + 3 jets would be more *normal* (>1) if a larger cone size and/or a larger jet p_T cutoff were used. But that's a LO problem; the best approach is to use the appropriate jet sizes/jet p_T's for the analysis and understand the best scales to use at LO (matrix element + parton shower) to approximate the NLO calculation (as well as comparing directly to the NLO calculation).









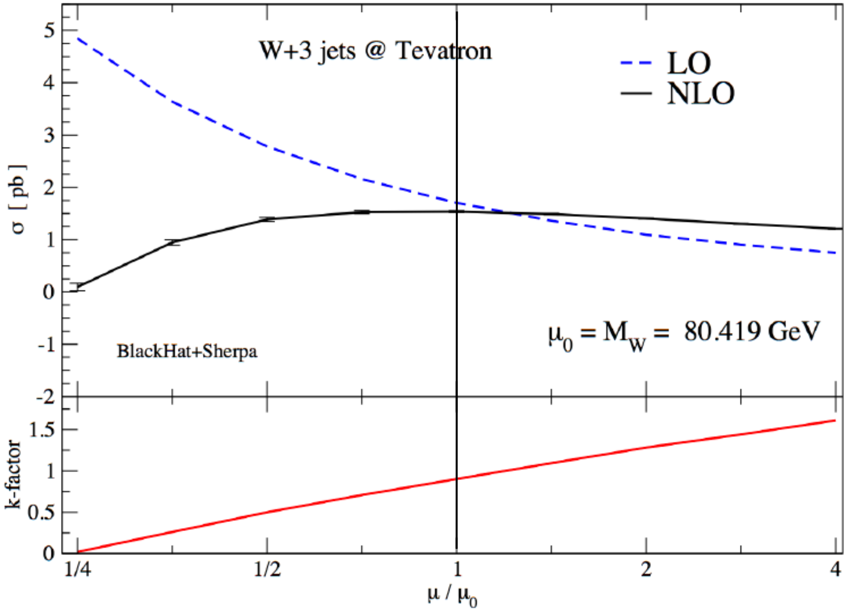


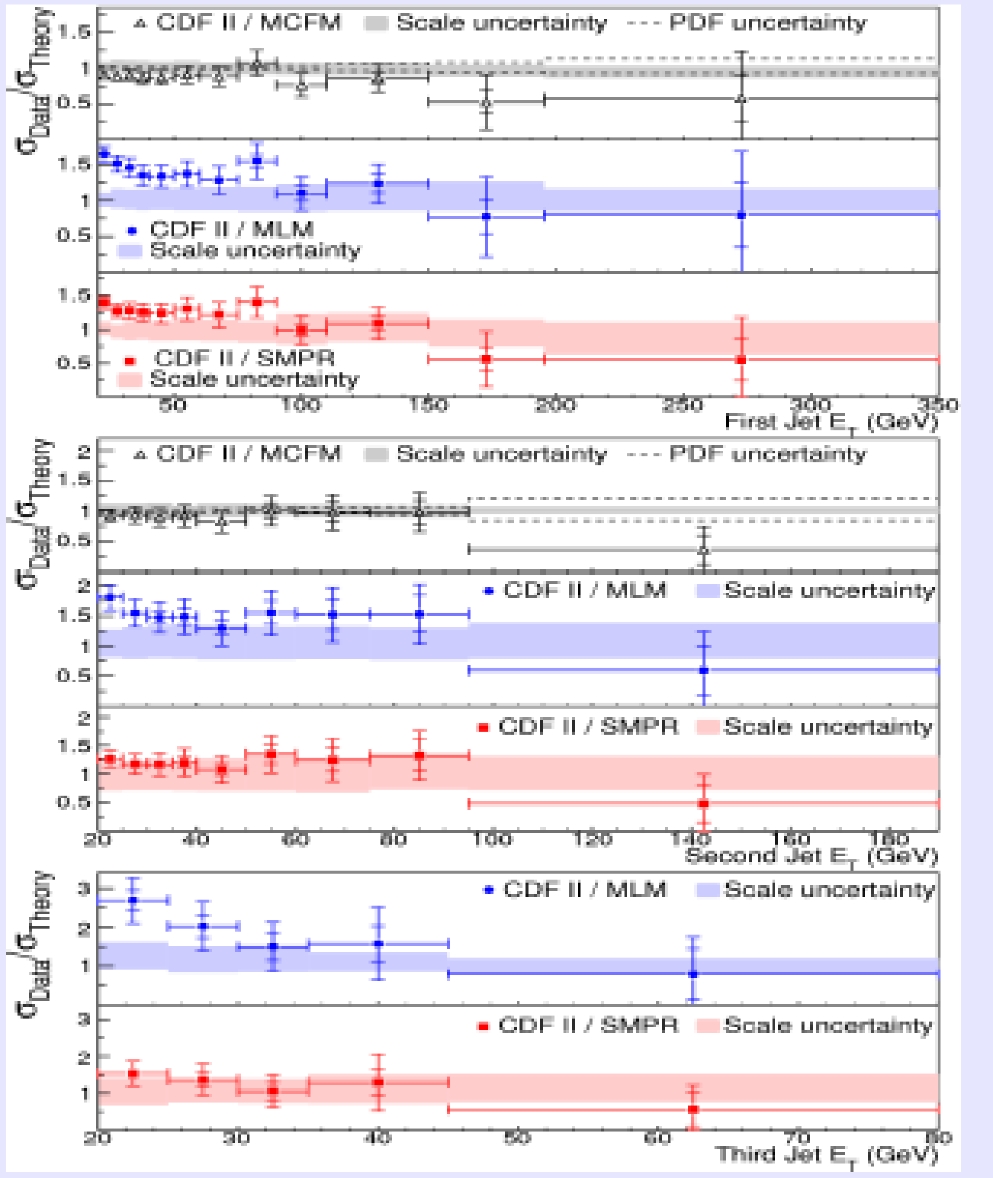
For 3 jets, the LO collinear singularity effects are even more pronounced.

NB: here I have used CTEQ6.6 for both LO and NLO; CTEQ6L1 would shift LO curves up

Scale choices at the Tevatron: W + jets

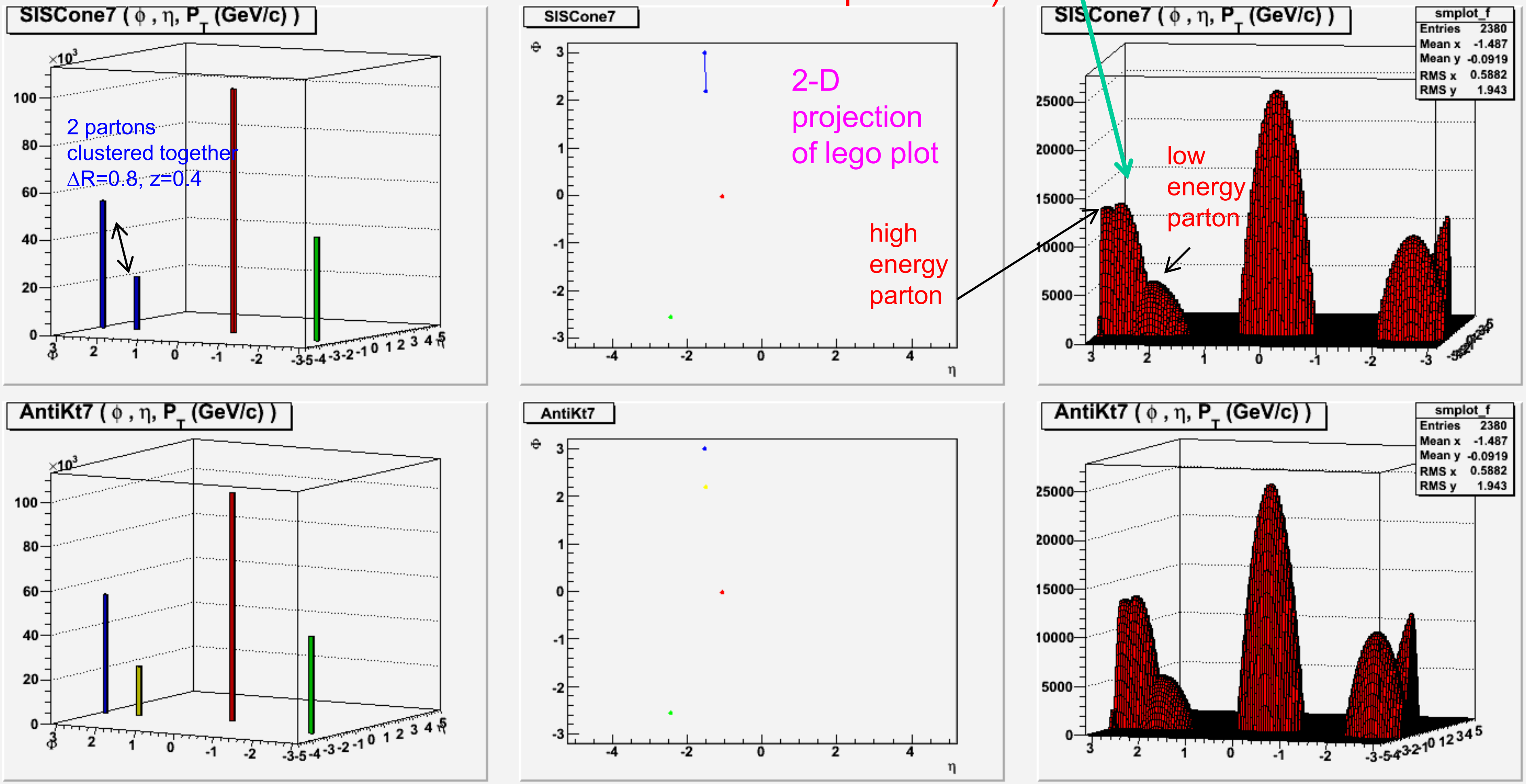
- At the Tevatron, m_W is a reasonable scale (in terms of K-factor~1)



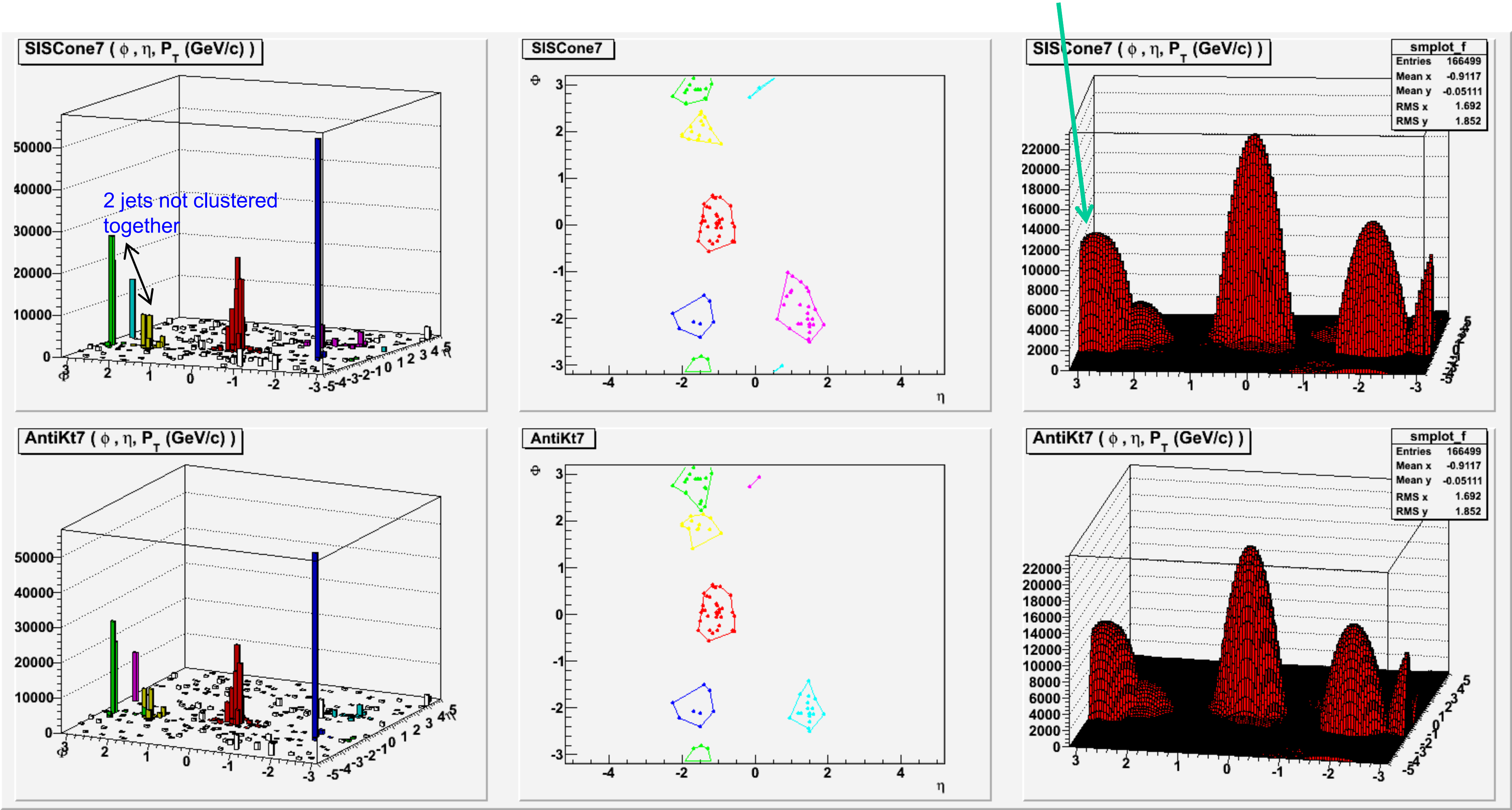


Now try ALPEN W + 3 parton event

SISCone solution including both partons (looking at inverted 2-D Snowmass potential)



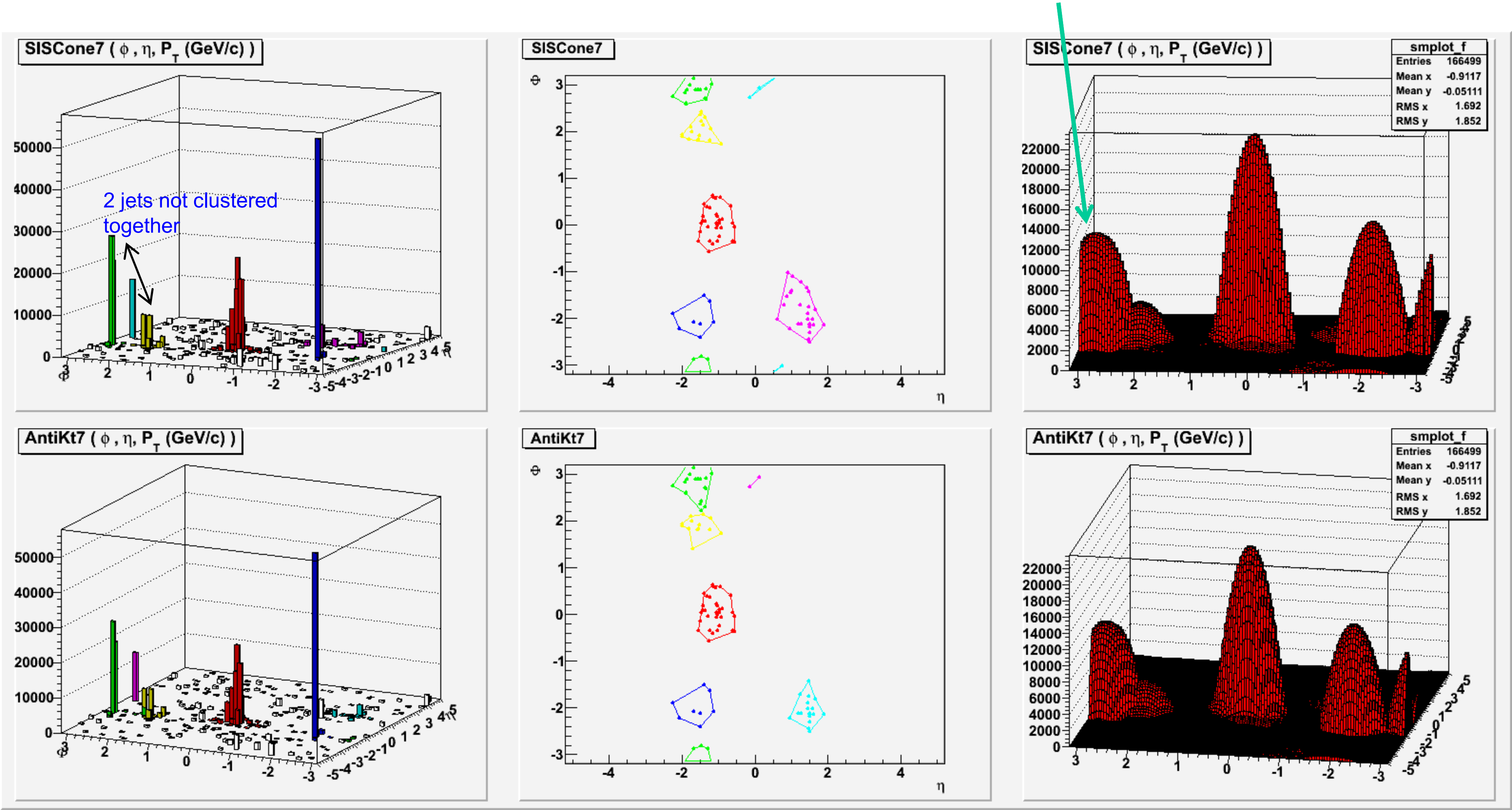
Same ALPGEN (+PYTHIA) event at topocluster level



disparu!

2 jets not clustered together

Same ALPGEN (+PYTHIA) event at topocluster level

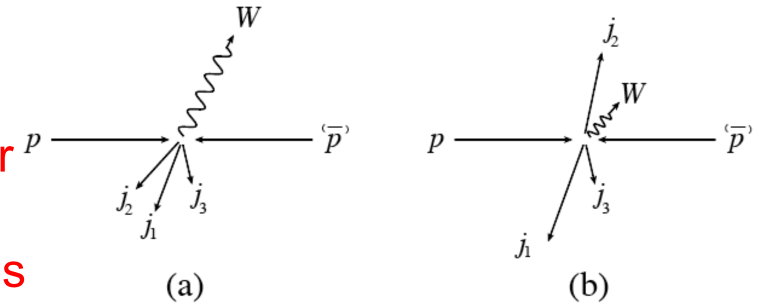


disparu!

2 jets not clustered together

Scale choices: what worked at the Tevatron for W + jets (m_W, E_T^W, $p^2_T{}^W+m_W^2$) won't at the LHC

If configuration (a) dominated, then as jet E_T increased, E_T^W would increase along with it. But configuration (b) is kinematically favored for high jet E_T's (smaller partonic center-of-mass energy); E_T^W remains small, and that scale does not describe the process very well



Note that now split/merge can become important as the partonic jets can overlap and share partons

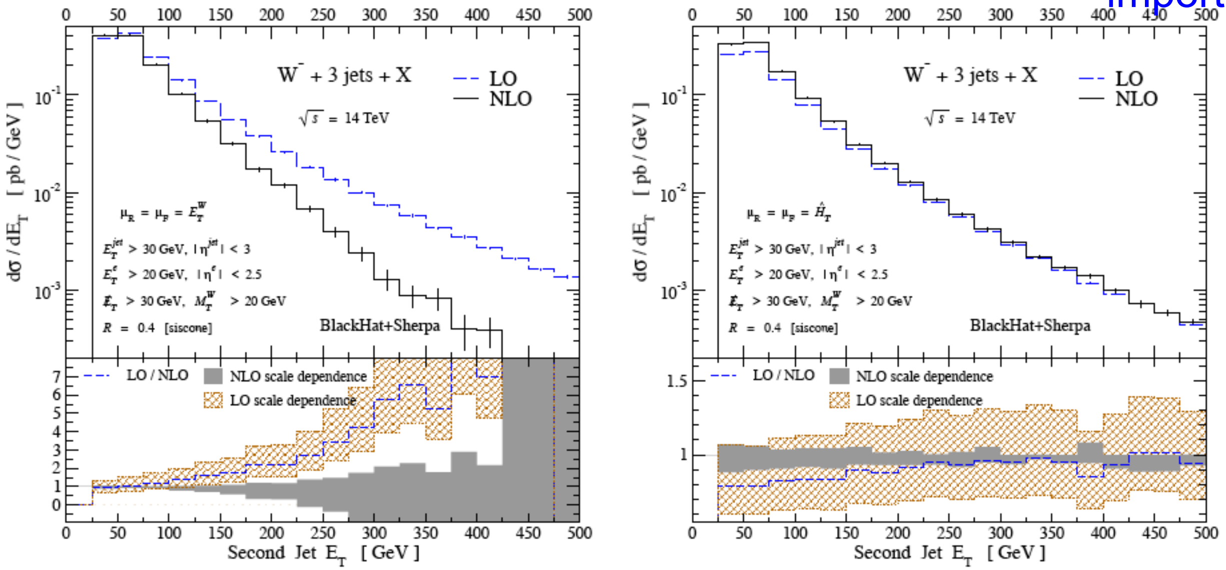


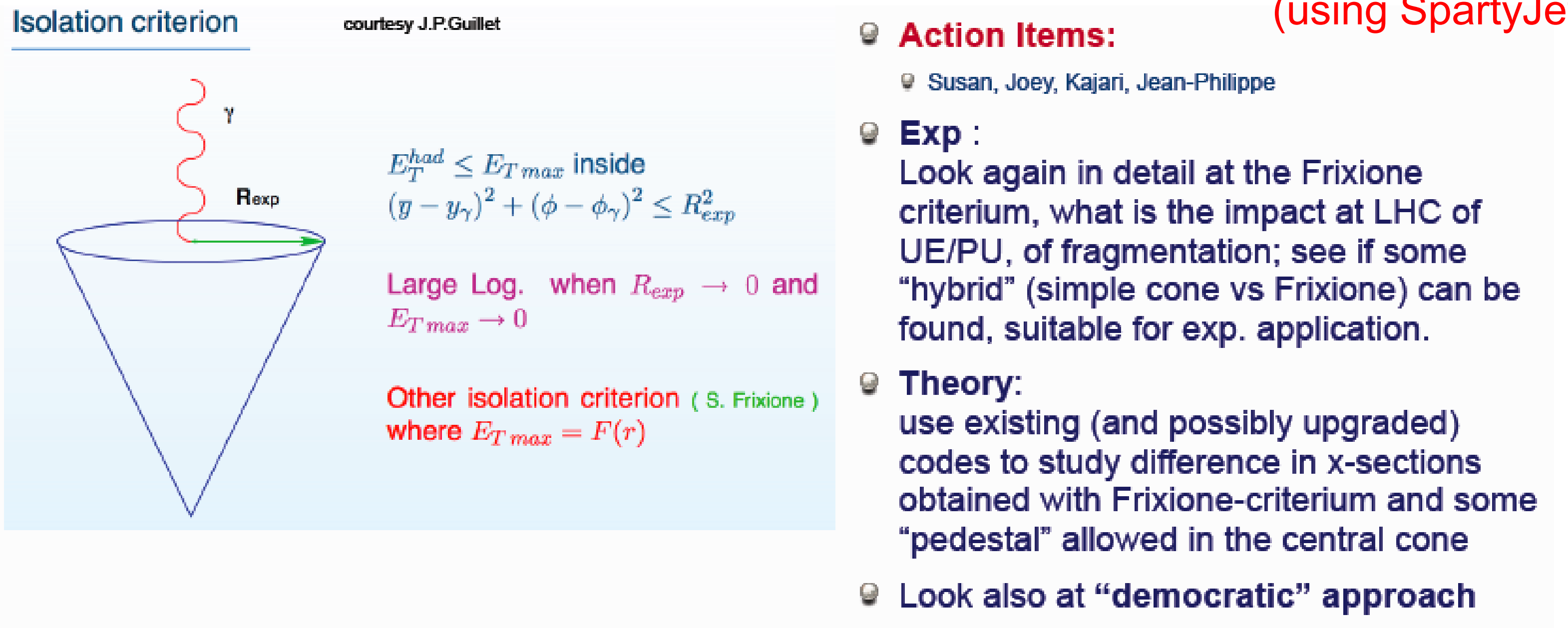
FIG. 9: The E_T distribution of the second jet at LO and NLO, for two dynamical scale choices, $\mu = E_T^W$ (left plot) and $\mu = \hat{H}_T$ (right plot). The histograms and bands have the same meaning as in previous figures. The NLO distribution for $\mu = E_T^W$ turns negative beyond $E_T = 475$ GeV.

Configuration b also tends to dominate in the tails of multi-jet distibutions (such as H_T or M_{ij}); for high jet E_T, W behaves like a massless boson, and so there's a kinematic enhancement when it's soft

arXiv:0907.1984

Aside: Photon isolation at the LHC

- From a theoretical perspective, it’s best to apply a *Frixione-style* isolation criterion, in which the amount of energy allowed depends on the distance from the photon; this has the advantage of removing the fragmentation contribution for photon production, as well as discriminating against backgrounds from jet fragmentation
- But most of the energy in an isolation cone is from underlying event/pileup
- At Les Houches, we started to develop (being continued by Mike Hance, Brian,…in ATLAS):
  - (1) an implementation of the Frixione isolation appropriate for segmented calorimeters
  - (2) a hybrid technique that separates the UE/pileup energy from fragmentation (using SpartyJet)



Isolation criterion

courtesy J.P.Guillet

$E_T^{had} \le E_{T\,max}$ inside $(y - y_\gamma)^2 + (\phi - \phi_\gamma)^2 \le R_{exp}^2$

Large Log. when $R_{exp} \to 0$ and $E_{T\,max} \to 0$

Other isolation criterion (S. Frixione) where $E_{T\,max} = F(r)$

- **Action Items:**
  - Susan, Joey, Kajari, Jean-Philippe
- **Exp** :
  Look again in detail at the Frixione criterium, what is the impact at LHC of UE/PU, of fragmentation; see if some “hybrid” (simple cone vs Frixione) can be found, suitable for exp. application.
- **Theory**:
  use existing (and possibly upgraded) codes to study difference in x-sections obtained with Frixione-criterium and some “pedestal” allowed in the central cone
- Look also at **“democratic” approach**